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TRACK TRAIN DYNAMICS ANALYSIS AND TEST PROGRAM - METHODOLOGY DEVELOPMENT FOR THE DERAILMENT SAFETY ANALYSIS OF SIX-AXLE LOCOMOTIVES

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16. ABSTRACT

A methodology is presented whose objective is to analyze the operational safety of six-axle locomotives. Its main elements are a locomotive model with corresponding data on suspension characteristics, a method of track defect characterization, and a method of characterizing operational safety. A user-oriented software package has been developed as part of the methodology and has been used to study the effect (on operational safety) of various locomotive parameters and operational conditions such as speed, tractive effort, and track curvature. As well, the operational safety of three different locomotive designs has been investigated. Other potential uses of the methodology, as well as further means of improvement, are examined.

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FOREWORD

This report, prepared by Dynamic Sciences Limited (DSL), under subcontract to Martin Marietta Corporation, Denver Aerospace, presents the results of the methodology development for the derailment safety analysis of six-axle locomotives. The work presented was performed from February 1980 through November 1980, using experimental data developed by Martin Marietta. This methodology development was conducted under contract NAS8-29882, which is administered by the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama, under the direction of Mr. Ismail Akbay. The contract is sponsored by the Federal Railroad Administration, Office of Rail Safety Research.

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TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	DESCRIPTION OF THE METHODOLOGY	3
	2.1 General Outline	3
	2.2 Input Parameters	7
	2.3 Output Results	11
	2.4 Software Overview	14
3.	APPLICATIONS, RESULTS, AND DISCUSSION	15
	3.1 Introduction	15
	3.2 Parameter Sensitivity Analysis	16
	3.3 Comparative Analysis	19
	3.4 Comments on the Methodology	22
4.	CONCLUSIONS AND RECOMMENDATIONS	24
5.	REFERENCES	26
	APPENDIX: 1 - Parameter Sensitivity Analysis	1-1
	2 - Comparative Analysis	2-1
	3 - Software Description	3-1
	4 - Mathematical Model Description	4-1

TABLE OF CONTENTS (CONTINUED)

FIGURES		Page
1	Methodology Overview	5
2	Nonlinear Model Degrees of Freedom	8
3	Basic Waveform of Track Geometry Defect for Vertical, Lateral, Cross-Level, and Track Gage Irregularities	10
4	Relation Between Derailment Coefficient (Wheel L/V Ratio) and Time Duration Requirement for Flange Climbing	10
1.1	Computed Sensitivity to Flange/Rail Stiffness	1-12
1.2	Computed Sensitivity to Flange Clearance . .	1-13
1.3	Computed Sensitivity to Wheel/Rail Adhesion .	1-14
1.4	Computed Sensitivity to Center Axle Mismatch.	1-15
1.5	Computed Sensitivity to Wheel Mismatch . . .	1-16
1.6	Computed Sensitivity to Wheel Conicity . . .	1-17
1.7	Computed Sensitivity to Primary Vertical Stiffness	1-18
1.8	Computed Sensitivity to Travel - Primary Vertical Suspension	1-19
1.9	Computed Sensitivity to Lateral Primary Free Play	1-20
1.10	Computed Sensitivity to Pedestal Friction . .	1-21
1.11	Computed Sensitivity to Limiting Force - Primary Vertical Dampers	1-22
1.12	Computed Sensitivity to Lateral Secondary Stiffness	1-23
1.13	Computed Sensitivity to Travel - Secondary Lateral Suspension	1-24
1.14	Computed Sensitivity to Limit Force - External Secondary Lateral Damper	1-25
1.15	Computed Sensitivity to Bolster Yaw Friction Factor	1-26
1.16	Computed Sensitivity to Tractive Effort . . .	1-27

TABLE OF CONTENTS (CONTINUED)

FIGURES		Page
1.17	Computed Sensitivity to Curvature	1-28
1.18	Computed Sensitivity to Amplitude of Track Defects	1-29
1.19	Computed Sensitivity to Wavelength of Track Defects	1-30
1.20	Computed Sensitivity to Number of Pulses of Track Defect	1-31
1.21	Computed Sensitivity to Type of Track Defect	1-32
1.22	Computed Sensitivity to Limit Force - External Secondary Lateral Damper	1-33
2.1	Peak Wheel L/V Ratio - 78 ft Wavelength Combined Defects	2-15
2.2	Peak Wheelset L/V Ratio - 78 ft Wavelength Combined Defects	2-16
2.3	Peak Truckside L/V Ratio - 78 ft Wavelength Combined Defects	2-17
2.4	Peak Wheel L/V Ratio - 39 ft Wavelength Combined Defects	2-18
2.5	Peak Wheelset L/V Ratio - 39 ft Wavelength Combined Defects	2-19
2.6	Peak Truckside L/V Ratio - 39 ft Wavelength Combined Defects	2-20
3.0	Computer Code Flow Chart	3-3
3.1	Structure	3-6
3.2	Structure	3-13
4.1	Side Elevation View of Model	4-24
4.2	End View of Model	4-25
4.3	Orientation of Coordinate System	4-26
4.4	Suspension and Wheel-Rail Forces	4-27
4.5	Secondary Lateral Stiffness Characteristics .	4-28
4.6	Linear Viscous Band (LVB) Model for Coulomb Friction	4-28

TABLE OF CONTENTS (CONTINUED)

FIGURES		Page
4.7	Primary Lateral Suspension Characteristics. .	4-29
4.8	Primary Vertical Suspension Characteristics .	4-29
4.9	External Damper Characteristic in the Vertical Primary Suspension	4-30
4.10	Wheel-Rail Friction Creep Characteristics . .	4-30

TABLES		
1.1	Definition of the Track Geometry Defect Used for the Parameter Sensitivity Analysis . . .	1-9
1.2	Summary of Parameter Sensitivity	1-10
2.1	Input Parameters	2-6
3.1	State Variables	3-26

EXHIBITS		
3.3.2.1	Vehicle Parameter Output	3-28
3.3.2.2	Track Defect Output	3-32
3.3.2.3	Operational Parameter Output	3-32
3.3.2.4	Safety Criteria Output	3-32
3.3.2.5.1	Available Output Variables	3-38
3.3.2.5.2	Sample Plot Output: Body Vertical Displacement (in.) Versus Time (s) . . .	3-39

CHAPTER 1

INTRODUCTION

The new generation of six-axle locomotives introduced in the last fifteen years has been attractive from many points of view, such as tractive effort, horsepower, costs, and ease of maintenance. However, under some operating conditions, in particular where the track routes are difficult or where the track strength conditions are low, some railroads experience difficulties in locomotive ride, track damage, and occasionally, derailments.

A serious problem developed when one particular design of six-axle locomotive became widely used on passenger trains. These normally run faster on curves than do regular freight trains. After nearly five years of operations and a total of 21 derailments(2)*, it became evident that the problem deserved special attention. Various tests were conducted in order to find a specific reason for the derailments, but no single cause was identified.

Recently, in an effort to provide a better understanding of the problem, and to develop locomotive acceptance procedures, extensive tests were run on specially prepared sections of track having geometry defects.(1) These tests were helpful in providing better information on typical levels of wheel-rail forces and critical levels of severity of track geometry defects. However, such methods are costly. As well, the test methods provide no mechanism to predict behaviour

* Numbers in brackets indicate references on Pages 25 and 26.

under operating conditions that are different from those of the test. It is obvious that some testing is required, but the use of analytical methods to support such testing will greatly improve the value of the results.

The methodology presented in this report provides a user-oriented analytical tool to predict operational safety of six-axle locomotives.

Experimentally verified characteristics of individual suspension elements, such as those obtained by Martin Marietta Corporation for locomotive trucks, are essential to the faithful representation of a locomotive. But the methodology is more than a mathematical locomotive representation; much information published by others is used for the characterization of several aspects such as track, wheel-rail interaction, locomotive characteristics, and derailment mechanisms.

CHAPTER 2

DESCRIPTION OF THE METHODOLOGY

2.1 GENERAL OUTLINE

Measures for assessment of operational safety are discussed in reference 3. Briefly, derailment can occur due either to flange climbing or to track gage spreading (vehicle roll-over does not normally occur).

Therefore a methodology to evaluate safety of a specific vehicle must be concerned with wheel-rail forces. Since wheel-rail forces are a result of dynamic behavior, the following three categories of parameters must be considered:

i) Locomotive parameters, describing the locomotive mass and suspension characteristics,

ii) Operational parameters, describing miscellaneous conditions such as speed, tractive effort, lateral coupler forces, as well as track curvature and superelevation, and

iii) Track geometry parameters describing deviations or defects from the nominal conditions with respect to cross-level, alignment, surface, or gage.

These parameters are used in a mathematical model to simulate the response of the locomotive to the specified conditions. The model is non-linear and therefore the solution consists of a time history for each of the system variables.

The safety of operation is assessed by monitoring selected variables in the model representing tendency to derailment.

The concept of the methodology is shown in Figure 1.

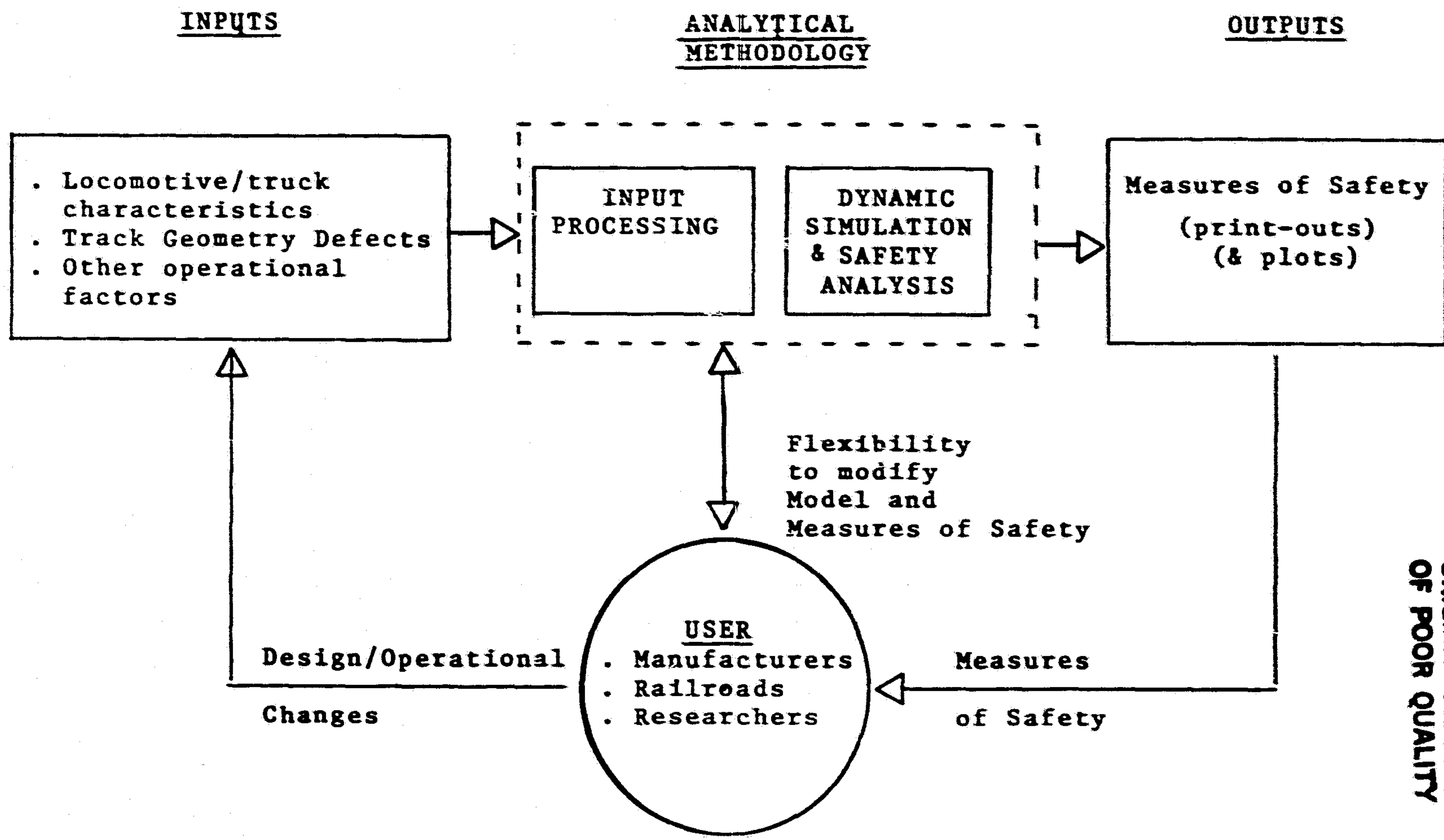

FIGURE 1 - METHODOLOGY OVERVIEW

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From the current state of knowledge, flange climbing, gage spreading, and permanent track damage can be monitored through the use of the following three measures of safety:

i) Single wheel L/V ratio representing the tendency for flange climbing,

ii) Net wheelset L/V ratio representing the tendency for lateral track panel shift,

iii) Truck side L/V ratio representing the tendency for rail rollover and gage widening.

In order to determine the time histories of these measures, a software package was developed to simulate the dynamic response of the locomotive. Monitoring of the measures of safety is performed automatically by the program in order to determine the maximum or peak values occurring during a simulation. Peak values of all three safety measures are determined for each of the 12 wheels, each of the 6 wheelsets, and each of the 4 "truck sides". A summary of these peak values is reported after completion of the simulation in a tabular form.

Options are provided for printing all important system variables at any instant for analysis of forces and displacements in the suspension, and for plotting time histories of any of these system variables.

2.2 INPUT PARAMETERS

2.2.1 Locomotive Parameters

In the methodology, a non-linear model is used to represent the locomotive. Figure 2 schematically delineates the 15 degrees of freedom represented in the locomotive model. The model is designed to be as simple as possible, and yet to include all important suspension characteristics derived from the tests performed by Martin Marietta on sample locomotive trucks.

Some important suspension features highlighted by the experimental test data were:

- vertical friction damping on the truck frame pedestals proportional to tractive effort, to wheel-rail steering forces, and to lateral thrust collar load on the roller bearings;

- external hydraulic dampers having asymmetric extension-compression characteristics;

- centerplate rotational friction proportional to centerplate load;

- secondary lateral friction damping proportional to tractive effort;

- spring bottoming at all interfaces.

Features not measured in the tests but included in the model are as follows:

MODEL HAS 15 DEGREES OF FREEDOM:

CARBODY = 5 DOF

FRAME = 2 DOF (EA)

WHEELSET = 1 DOF (EA)

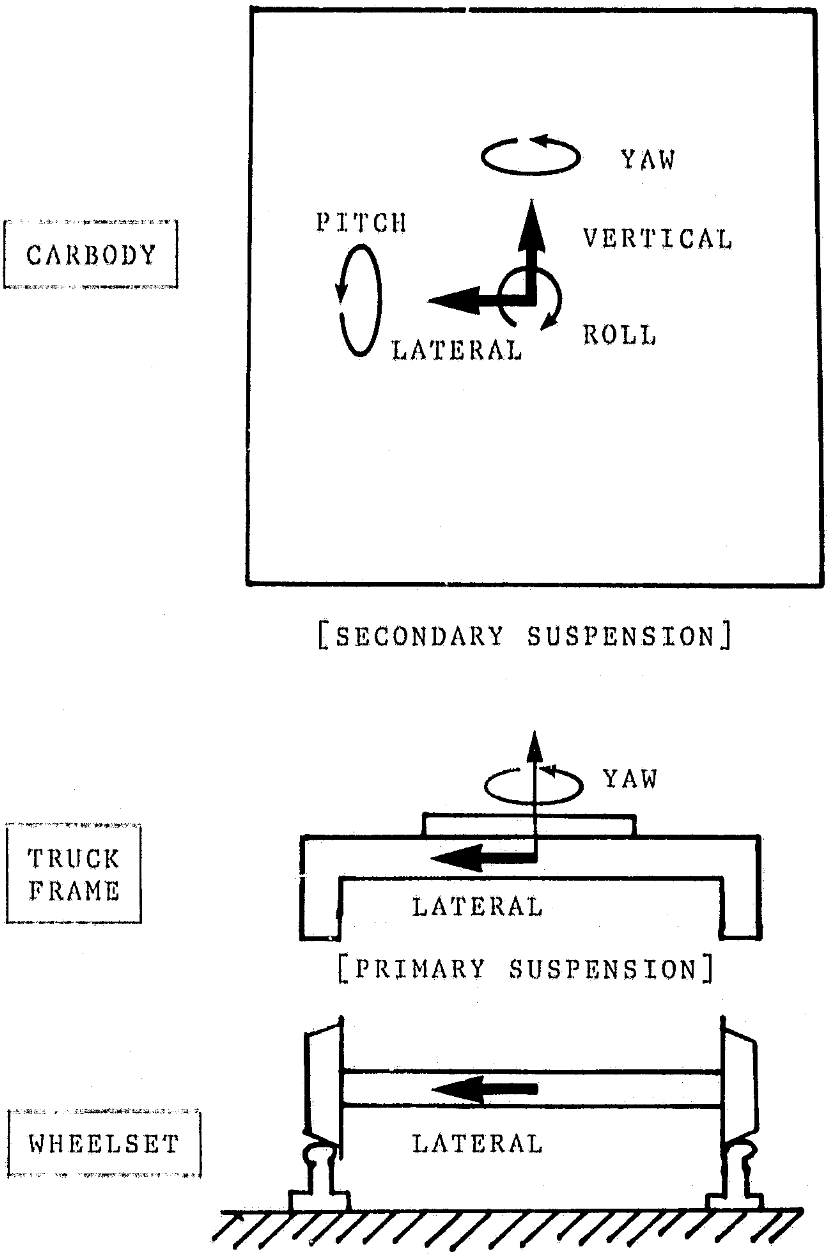

FIGURE 2 - NONLINEAR MODEL DEGREES OF FREEDOM

- Flange contact,

- Non-linear wheel-rail creep forces dependent on instantaneous wheel loads,

- Unequal wheel diameters on different axles,

- Unequal diameters of wheels mounted on the same axle (tape size mismatch).

The complete list of parameters is included in the software description (Appendix 3).

2.2.2 Operational Parameters

Parameters which normally vary during operation include speed, tractive effort, lateral components of coupler force, and wind loads. For convenience, nominal track curvature and superelevation are also included as operational parameters.

2.2.3 Track Geometry Defects

Four types of track geometry defects are modelled:

1. Cross-level
2. Lateral (or alignment of both rails)
3. Vertical (or surface of both rails)
4. Track gage variations.

For each of the types above, defects can be specified in the form of transient pulses, as shown in Fig. 3. Any number of these pulses can be specified along a section of track. The basic waveform is a sinusoid having an amplitude and a wavelength characteristic. Combined defects can be

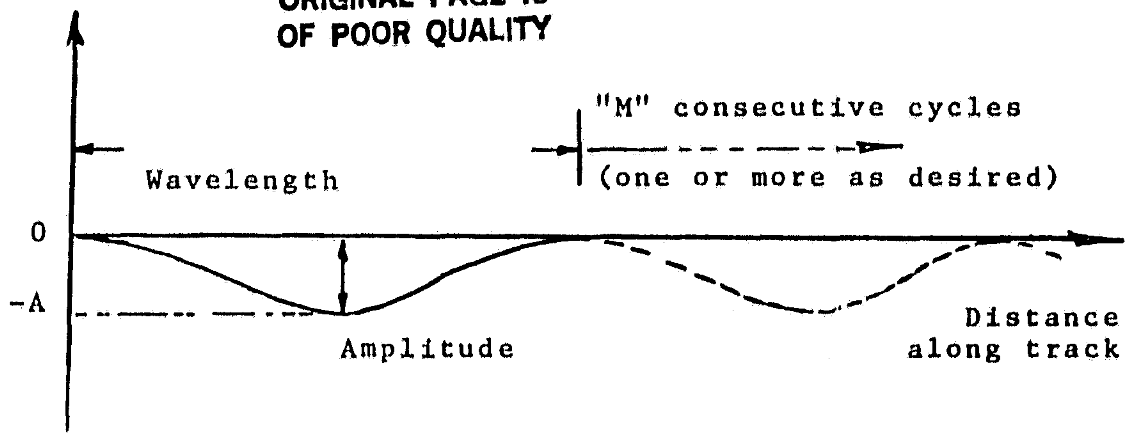

FIGURE 3 - BASIC WAVEFORM OF TRACK GEOMETRY DEFECT FOR VERTICAL, LATERAL, CROSS-LEVEL, AND TRACK GAGE IRREGULARITIES.

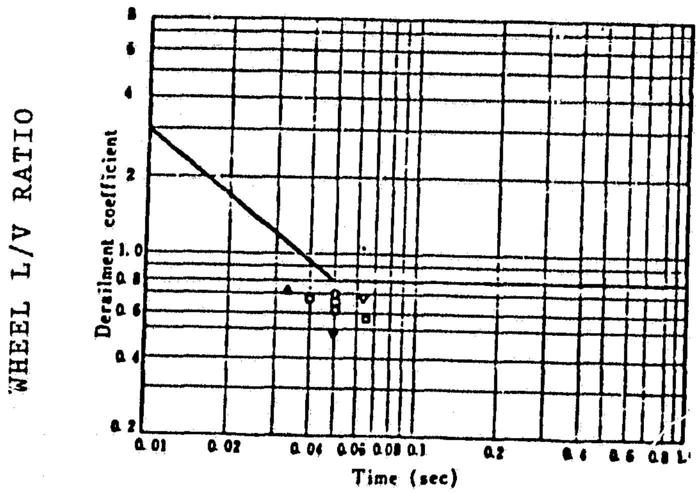

FIGURE 4 - RELATION BETWEEN DERAILMENT COEFFICIENT (WHEEL L/V RATIO) AND TIME DURATION REQUIREMENT FOR FLANGE CLIMBING.

(Extract from "Outline of 250 Km/h Test run for the new Tokaido line" by Y. Ishihara. J.N.R. bulletin)

specified by superposition of defects in any of the four types listed above. As well, other waveforms can be obtained by superposition of different wavelengths (i.e. Fourier components).

Although not specifically programmed in its present form, minor modifications would allow arbitrarily defined track defects.

2.3 OUTPUT RESULTS

Since the model computes time histories of all wheel-rail and suspension forces, there is complete flexibility in the selection of measures of safety.

However, judging from the technical literature, only three measures of safety have received enough attention both theoretically and experimentally to justify inclusion in the methodology at this stage. These measures result from three specific derailment (or track damage) mechanisms as follows:

2.3.1 Wheel Climb

The primary indicator of wheel climbing is the ratio of lateral to vertical load on an individual wheel. This is the oldest known mechanism for derailment.(4) Under normal operating conditions, the potential for flange climbing is practically nil when the wheel L/V ratio is less than 0.8. However, because the actual wheel climbing action depends on other factors, such as flange angle, wheel-rail coefficient of friction, and wheel-rail angle of attack, higher values than 0.8 may be sustained without derailment.(10)

One aspect considered in the analysis is the fact that higher values of L/V can be sustained without derailment provided the time duration is short. The generally accepted figure for time duration is 50 msec, as shown in Fig. 4. In the methodology this effect is implemented by the use of a simple "running average" over 50 msec. Since this time duration is adjustable in the model, values other than 50 msec. can be specified.

2.3.2 <u>Lateral Track Panel Shift</u>

This mechanism consists of a shift of the track structure (rails and ties) laterally with respect to the ballast. Although not a derailment mechanism in itself, it is included in the methodology as a mode of track failure. Experimental work in this area indicates that the tendency for track panel shift depends on the ratio of lateral to vertical axle load or net "wheelset L/V ratio".(11)

Critical values for wheelset L/V ratio depend on many track design details such as tie type, size, and spacing, as well as ballast type and shoulder width. Track panel strength is also quite sensitive to the degree of ballast consolidation. Typical critical values vary from 0.3 on newly worked track, to 0.7 or more on well compacted track.(3,11)

2.3.3 <u>Gage Widening by Rail Rotation (Rail Rollover)</u>

When the track gage becomes excessively large, (typically 3½ inches wider than the standard track gage), it is possible for a wheel to drop inside the rail onto the ties. Visual observations of the remaining trackage after derailments have sometimes revealed this condition.

Theoretically, two mechanisms can produce the lateral railhead motion required to obtain the wide gage: first, lateral shift of the rail base and secondly roll of the complete rail section as a rigid assembly (neglecting small distortions of the rail section).

Very little experimental data exists on the critical levels of load required to produce wide gage under typical "in-service" conditions. The problem is quite complex when considering the simultaneous action of many wheels of a truck under the effect of rail torsional stiffness. This is an area of current research by the AAR.(5,9)

There is, however, one aspect that must be considered as a potential track damage mechanism. This is the total lateral to vertical load ratio exerted by a truck on one rail called "Truck Side L/V Ratio". Under high lateral loads, the resultant force vector on the rail can point outside the edge of the rail base. From this point on, rail roll-over is only prevented by the restraint from the spikes.

Critical values for derailment depend on the "height to width ratio" of the rail section, as well as on the strength of the spikes or fastening system. In practice, an acceptable truck side L/V ratio would vary between 0.5 for an unrestrained rail to (0.5 + 20,000/wheel load (lb)) for wooden ties and new spikes(3).

2.4 SOFTWARE OVERVIEW

The methodology uses a software package written in FORTRAN. The program is named DSL-2, for "Dynamics of Six-axle Locomotives", and was developed on a CDC Cyber 174 computer.

Many features of the program were designed to be user-oriented. Input parameter names and units were chosen to be those normally used by the railroad industry. The program operates interactively on a remote terminal with respect to input and output data.

To facilitate the handling of the locomotive parameters, of which there are many, predefined or "canned" sets are used in the program and a facility is provided to alter any parameter under interactive control from the terminal.

All input parameters are "echoed" for checking purposes, and all output formats are labelled with respect to date, time, run number identification, and program revision number.

Concerning software structure, the program is completely modular, containing over forty subroutines which provide flexibility with respect to program changes.

Program running costs are reasonable, considering the complexity of the model. On the CDC Cyber 174 computer, execution requires a maximum of 11 seconds of CPU time for each second of real time simulation. Program execution requires 18K words of memory. Typical running costs on a commercial time sharing system vary between one and two dollars per second of real time simulation.

More detailed software documentation is provided in Appendix III.

CHAPTER 3

APPLICATIONS, RESULTS, AND DISCUSSION

3.1 INTRODUCTION

The methodology can play an important role as a predictive technique, as well as a test support tool in many areas of rail safety. Typical applications are:

- assessment of the importance of specific suspension design details;

- comparison of different locomotive designs;

- determination of appropriate maintenance standards on locomotive suspension elements (e.g. shock absorbers);

- determination of acceptable track geometry defects and minimum track strength requirements;

- investigation of specific derailment mechanisms.

In order to demonstrate how the methodology can be used, two distinct analyses were performed as follows. The first analysis consisted of an extensive parameter sensitivity study on a selection of twenty parameters relating to suspension design, operational conditions, and track geometry defects. The second analysis consisted of comparing the relative safety performance of three locomotive designs subjected to severe track geometry defects. Suspension parameters defining the three locomotives are based on Martin Marietta test data for the SDP-40F, the U-30C, and the E-8 locomotive trucks.(12,13,14)

3.2 PARAMETER SENSITIVITY ANALYSIS

3.2.1 Description

In this study, a reference or "Base Case" is selected, fixing all required input parameters. Evaluation of the safety performance is made by recording the peak or maximum value of each of the three measures of safety. (It is emphasized here that only one peak value is retained for each measure of safety without regard to the wheel or wheelset position at which it occurred.) Parameters are then changed one at a time, to determine their effect on the safety of operation.

The reference case is chosen to be the SDP-40F locomotive equipped with "New HTC"* trucks, running on a 3-degree curve at a normal passenger speed of 65 mph.

A single cycle of track geometry defect is used, containing deviations in cross-level, alignment, and surface, and whose severity is set at the acceptable limit for class 4 track on curves. The wavelength of the defect is chosen to be 78 ft., similar to that of the "Perturbed Track Tests".(1)

Having defined all input data, a set of twenty parameters were selected for the sensitivity analysis.

3.2.2 Results

The observations listed below represent the most significant findings from the sensitivity analysis (related to the new HTC truck design). However, most observations are of a sufficiently general nature that they probably apply to other locomotive designs. Details of procedures and numerical values are given in Appendix 1.

*Modified HTC design (>Jan 1977): Soft rubber bolster springs, lateral (secondary) shock absorber, steel pedestal liners (see Table 2.1).

a) The severity of the track geometry defect is the most important factor governing the peak values of the measures f safety. Compared to those obtained for steady state values on a 3 degree curve (wheel L/V = .29, wheelset L/V = .07, truck side L/V = .18), the presence of a severe geometry defect significantly increases the peak values. The safety measure which increases most drastically due to the presence of the defect is the wheelset L/V representing the potential for lateral track panel shift.

b) Of the three components included in the composite track defect used (i.e. surface, cross-level and alignment), the alignment component produces the largest peak values of the safety measures when used alone.

c) For a given amplitude of defect, the wavelength has a large influence. Of all the wavelengths studied (between 39 ft and 118 ft), the shorter wavelengths give the largest peak values of safety measures.

d) Wheel rail adhesion has a large influence on "wheel L/V" and "truck side L/V", but little effect on "wheelset L/V".

e) Wheel size differentials have an effect on the safety measures. However, small mismatches in wheels of the same axle (i.e. from left to right) have a larger effect than differences between axles of a truck.

f) Conicity of the wheel treads has a large influence on the safety measures. Increased conicity (e.g. worn wheels) can reduce significantly the "wheel" and "truck side" L/V ratios. However, it was noticed that the peak value of wheelset L/V increases and begins to occur on the trailing axle of the trailing truck.

g) No individual suspension damping element was found to have a major effect by itself. This is probably because there are several sources of damping on the new HTC truck, which all contribute to the overall system (e.g. pedestal friction, bolster friction, external vertical dampers, and lateral hydraulic dampers).

3.3 COMPARATIVE ANALYSIS

3.3.1 Description

The objective of this study was to demonstrate how the methodology can be used to compare different locomotive designs. Such comparisons can be used, for example, to highlight problem areas and possible solutions on existing locomotives, or to examine at the design stage the projected performance of new locomotives.

In this analysis, three locomotives are compared, for which suspension characteristics are available from the Martin Marietta Corp. truck test data(12,13,14). The three locomotives are the SDP-40F equipped with New HTC (soft) trucks, the U-30C, and the E-8 locomotive. In order to provide realistic operational conditions, the following operational parameters are used for the simulated test.

- 3 degree curve,
- 6 inches superelevation,
- speed range 40 - 65 mph, and
- single track geometry defect at the allowable limit of FRA Class 4 track.

Similarly to the sensitivity analysis, a combined defect is used, having components in cross-level, alignment and surface.

In order to show possible dependence of the comparative performance on the type of track defect, two different wavelengths of track defect are used. The first is set at 78 ft, similar to the PTT[1] procedure, and the second is set at 39 ft, representing a standard rail length.

Comparative performance of the three locomotives is measured by the maximum values of each of the three measures of safety for the speed range considered.

3.3.2 Results

It must be emphasized at this point that the comparative analysis results only represent locomotive performance under a limited range of operating conditions. As well, the results only show maximum or peak values of the measures of safety and do not necessarily represent average or steady state values.

Since the model has not been test verified, the absolute values of measures of safety may be questionable. However, the relative effects of parameter variations are considered valid.

Details on procedures and numerical results are presented in Appendix 2. However, the following observations were made from the comparative analysis resul s.

a) Peak wheel L/V ratios (i.e. flange climbing) for the three locomotives are not substantially different from each other, and are generally lower than currently accepted critical values for derailment.

b) Peak wheel L/V ratios do not increase significantly as the speed is varied from 45 to 65 mph.

c) Significant differences are found between the three locomotives when considering wheelset L/V ratio (i.e. track panel shift) resulting from the long wavelength defect considered (78 ft.), when operating at 65 mph (i.e. above the equilibrium speed). At this speed the U-30C locomotive showed a significant increase in wheelset L/V, when compared to the SDP-40F and E-8. However, simulations indicate that substantial improvements can be made to the U-30C by the addition of extra dampers in the secondary lateral suspension (i.e. between the truck and car body).

d) Operating speed has a major effect on the peak wheelset L/V ratio towards the outside rail (i.e. track shift outwards on curve). Above the equilibrium speed, peak wheelset L/V ratios increase relatively sharply on the U-30C and the SDP-40F, but less on the E-8.

e) Simulation results indicate that the peak wheelset L/V ratio resulting from maximum allowable class 4 defects reach the critical values for unconsolidated track conditions.

3.4 COMMENTS ON THE METHODOLOGY

The purpose of this section is to discuss briefly various aspects considered in the methodology as they reflect real life conditions. As well, it is desired to highlight various modelling aspects regarding track and locomotive characteristics as well as derailment safety which are considered desirable as enhancements. This will help to provide a better understanding of the scope and present limitations of the approach.

In the study of derailments, the investigation of transient response is more pertinent than that of steady state response because isolated large amplitude track defects are more representative of actual track conditions which cause derailments. Although it is possible to represent measured track data, the use of idealized waveforms allows a better understanding of the phenomena involved. Furthermore, no information is available on the types of track defects which actually led to the reported derailments.(2)

The present model features most of the important locomotive suspension characteristics covered by the test data. There are a few items however for which there is no experimental data. Although not believed to be critical at this stage, it would be desirable to obtain experimentally validated data. These are:

a) roller bearing lateral friction;

b) measured overtravel stop characteristics;

c) effects of side-bearings on centreplate rotational stiffness;

d) locomotive body torsional stiffness;

e) non-linear rubber characteristics;

f) coupler stiffness and damping characteristics with respect to lateral and vertical motions.

Considering the measures of safety, the approach has been to compute peak values of the L/V ratios. The user then has to make a judgement on the actual potential for derailment or track damage. It would be desirable to build into the methodology a set of safety criteria, indicating whether the level of safety is acceptable or not. To do this, a flange climbing model would have to be incorporated in the model. To predict track damage, the algorithms would require changes because the critical values of many of the measures of safety are dependent upon the level of the vertical wheel load.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

A methodology has been developed to compare the safety of operation of different locomotive designs. Its main elements are a method of characterization of track defects, a locomotive model with corresponding data on suspension characteristics, and a method of characterizing operational safety. The methodology has been used to study the effect of various locomotive parameters and operational conditions as well as to compare the operational safety of three different locomotives.

Judging from the results to date, the methodology gives a faithful representation of locomotive behaviour. It has been possible to duplicate analytically many trends observed during previous experimental tests. It has also been possible to simulate little-understood behaviour observed in actual locomotives such as the occurrence of large dynamic forces on the trailing axle of the trailing truck. It is evident that the approach taken is worth pursuing.

The methodology can be used in other areas of rail safety not specifically investigated in this report. It can be used for example in refining information on acceptable track geometry defects, whether the defects are taken individually or in combinations; it can also be used in the determination of safe operating speeds. It is believed that the methodology can play an important role in the investigation of derailments and in the study of specific derailment mechanisms. Another potential application is in the planning of field experimentation, including the selection of test conditions, the design of instrumentation procedures, and the development of safety criteria.

Although the present state of development of the methodology makes it a readily usable tool, many areas leave room for improvements, as discussed in the previous section. Briefly, improvements are possible in the track characterization, including the use of actual track defects, in the addition of other suspension features (e.g. side bearings), and in the definition and inclusion of safety criteria.

Although exhaustive checks have been conducted to insure model validity, validation tests should be run to define simulation accuracy. PTT[1] data is recommended for use in this validation. Validation is important to ensure that significant factors have not been neglected in the design of the model and in the definition of the measures of safety. It is emphasized that a methodology validation should ideally extend into a range of operating conditions at or beyong limits of safety.

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Appendix 1 - Parameter Sensitivity Analysis

	Pg
1.1 Scope of the Study	1-1
1.2 Sensitivity of Selected Parameters	1-3
1.3 Discussion on Parameter Sensitivity	1-5

APPENDIX 1

PARAMETER SENSITIVITY ANALYSIS

1.1 SCOPE OF THE STUDY

An analysis was made to determine the sensitivity of the three measures of performance (L/V ratios) to various locomotive and track defect parameters. Of the three locomotives under study (Appendix 2), the SDP-40F with new HTC trucks was selected for sensitivity analysis since it is more common than either of the others.

Except where otherwise noted, a standard track defect and set of operational conditions were used for the analysis. The defect, shown in Table 1.1, is a combination of crosslevel, lateral, and vertical misalignments having amplitudes equal to the maximum limit of FRA Class 4 track standards. This composite defect excites all modes of the dynamic system. The wavelength of the defect was chosen to be 78 feet, which is the same as that used in the Perturbed Track Test (PTT).

The standard operating condition was selected to be:

i) 65 mph locomotive speed,
ii) 3 degree curve with 6 inches superelevation, and
iii) 9000 pounds of tractive effort.

Statistically, it has been found that many derailments involving SDP-40F locomotives have occurred at medium speeds on 3 degree curves.(2) With 6 inches of superelevation, the maximum allowable vehicle speed on this curve would be 65 mph based on the conventional railway practice of a maximum of 3 inches cant deficiency. The 9000 lbs. of tractive effort

was representative of what might be required to pull a conventional passenger train at 65 mph through a 3 degree curve.

The parameters selected for the analysis were those which could vary in actual service (for example: wheel/rail adhesion, defect amplitudes, flange clearance), those which might be affected by maintenance practice (for example: center axle diameter mismatch, external damper limiting forces), and those which could be changed with minor redesign to the equipment (for example: spring stiffnesses and travels).

The ranges of the parameter variations were selected as those which could be found in railway service, or those which might be achieved within the existing design. For example: flange/rail clearances could vary from 0.30" to 1.50", either because of deviations in track gauge which are within the acceptable FRA track specifications, or because of intentional gauge widening in curves.

A total of 21 parameter sensitivities were evaluated which fall into one of the following six categories:

- wheel/rail interface
- wheelset geometry
- primary suspension
- secondary suspension
- track defect geometry
- operating conditions

The analysis was made by changing only one parameter, or only one set of parameters which in combination produce a single change to the system, at a time. For example: to study the influence of degree of curvature only, both the curvature and superelevation parameters were varied together, so as to have the same net lateral force due to centrifugal acceleration acting on the locomotive.

1.2 SENSITIVITY OF SELECTED PARAMETERS

The following section presents the results and a brief discussion of the parameter sensitivity analysis performed. It should be noted that the results pertain to the evaluation of safety measures (L/V ratios) and consequently, the trends indicated may not be exploitable in actual locomotive designs because of other considerations such as the vehicle ride quality, hunting stability, or wear.

The results are given in graphs (Figures 1.1 to 1.21), with the three L/V ratios (individual wheel, wheelset, and truck-side ratios) plotted versus the parameter being studied. The L/V ratios shown in figures were the maximum values which occurred in a given simulation run and are not specifically related to a particular wheel or wheelset. However, in general, it was found that the highest wheel L/V occurred on the outer wheel of the lead axle of the front truck; that the highest wheelset L/V was on the leading axle of the rear truck; and that the highest truck-side L/V was found on the outer side of the rear truck.

Because only one parameter was varied at a time, the results sometimes showed only a small sensitivity to that parameter, whereas the sensitivity might be greater for a different set of conditions or for other values of the other parameters. (e.g. lateral hydraulic dampers in the secondary are more effective when the tractive effort is small as shown in Fig. 1.22).

Tables 1.2 and 1.3 are a qualitative summary of the results of the parametric analysis. The sensitivity of each parameter is described as being either small, moderate, or large for each of the three L/V ratios. "Small" sensitivity is defined when the variation between the maximum and minimum L/V ratios is less than 0.05; "moderate" sensitivity is between 0.05 and 0.10; "large" sensitivity is for variations greater than 0.10.

1.3 DISCUSSION ON PARAMETER SENSITIVITY

1.3.1 Wheel/Rail Interface Parameters

Three parameters in this group were studied: Flange/rail stiffness, flange clearance, wheel/rail adhesion. The flange stiffness which attenuates the lateral forces from the wheels to the ground, had only small effects on the L/V ratios. This is because the primary and secondary lateral suspensions of the locomotive are much softer than the range of rail stiffnesses considered, and hence the vehicle stiffness has a predominant influence on the L/V ratios.

Flange clearance influences the rolling radius difference between wheels and angle-of-attack of the wheelset, and as a result, the creep forces. By increasing the flange clearance, the creep forces increase which tends to steer the wheelset to a more radial position and thus to decrease the L/V ratios.

Wheel/rail adhesion is directly related to the creep forces, and provides a strong influence on the steering of the wheelset and hence the wheel L/V ratios.

1.3.2 Wheelset Geometry Parameters

Wheel conicity, center-axle mismatch, and wheel side-to-side mismatch were studied in this group of parameters. Both wheel conicity and wheel side-to-side mismatch have large influences on the L/V ratios, which is due to these parameters having a direct effect on the creep forces at the wheels.

Center-axle mismatch primarily changes the vertical load distribution within the truck, and has little effect on the steering moments of the truck. As a result, the L/V ratios do not vary significantly with center-axle mismatch.

1.3.3 Primary Suspension Parameters

Five parameters were studied in this group: primary vertical travel and spring stiffness, pedestal friction, the limiting force of the external primary suspension dampers, and the lateral free play between the axle and journal boxes. It was expected that the L/V ratios would be affected by the first four of these parameters as a result of any vertical wheel unloading. For example, suppose a wheelset experiences a downwards vertical dip in the track. If the wheelset is restrained from following the dip due to the primary suspension, particularly for the case of suspension bottoming, off-loading of the wheel/rail vertical force would occur.

The sensitivity analysis for these parameters showed only small or moderate changes in the L/V ratios. This is because no substantial vertical off-loading occurs as a result of the track defect for the range of parameters selected. In addition, there is always some vertical damping present in the system (either due to pedestal friction or to external dampers, or both) which tends to control suspension-bottoming.

Only small sensitivities of the L/V ratios were found for variations in the lateral free play between the axle and journal boxes. This is because only a small amount of energy is removed from the system as a result of the friction between the axle and rollers in the journal boxes and the lateral free play.

1.3.4 Secondary Suspension Parameters

The four parameters studied in the secondary suspension were lateral secondary travel and spring stiffness, the limiting force of the external secondary damper, and the bolster yaw friction factor. The first three parameters are related directly to the lateral dynamic forces which result from track defects, and showed moderate effects on the L/V ratios. These effects were noticeable at low values of the parameters, where suspension-bottoming and thus large lateral forces can occur.

The bolster yaw friction factor principally influences the truck swivel angle and hence the angles-of-attack of the wheelsets. For the range of friction factor studied, there were no appreciable changes in these angles and hence in the L/V ratios.

1.3.5 Operational Parameters

Two operational parameters were varied: degree of curvature and tractive effort. As discussed earlier, curvature and superelevation parameters were changed simultaneously such that there was no net change in the lateral force on the vehicle due to centrifugal forces. The influence on the L/V ratios would then only be due to the degree of curvature. The results showed a small trend of increasing L/V ratios with degree of curvature; this is due to the increasing angles-of-attack of the wheelsets. However, because the curvatures were large, the trucks freely negotiated the curves without flanging of the trailing axles, and hence the angles-of-attack did not change significantly.

Tractive effort principally provides suspension damping due to friction in the pedestals and secondary suspension traction stops. The effects on the L/V ratios are small, as there are other sources of damping present in the system which control the motions of the wheelsets and secondary suspension.

1.3.6 Track Defect Geometry Parameters

The amplitude, wavelength, number of track defects, and the type of track defects were studied in this group.

It was found that the L/V ratios are highly sensitive to variations in these parameters. This is to be expected, since these parameters are directly related to the severity of the system forcing function.

TRACK GEOMETRY DEFECT CHARACTERISTICS

DEFECT No. 1

COMPONENT	TYPE	AMPLITUDE * (in)	WAVELENGTH (ft)
1	CROSS-LEVEL	-1.25	78
2	LATERAL	1.5	78
3	VERTICAL	-1.375	78

TABLE 1.1 - DEFINITION OF THE TRACK GEOMETRY DEFECT USED FOR THE PARAMETER SENSITIVITY ANALYSIS.

*Note: The following gives an equivalent description of the composite track geometry defect, in terms of the individual rails.

Vertical, outer rail - 2 inches down,
Vertical, inner rail - 3/4 inch down,
Lateral, both rails - 1½ inch to outside of curve.

PARAMETER*		SENSITIVITY #		
		WHEEL L/V	WHEELSET L/V	TRUCK-SIDE L/V
1.	Flange/rail stiffness	Small	Small	Small
2.	Flange clearance	Moderate	Small	Small
3.	Wheel/rail adhesion	Large	Small	Moderate
4.	Centre-axle mismatch	Moderate	Small	Small
5.	Wheel mismatch (right-to-left)	Large	Large	Large
6.	Wheel conicity	Large	Large	Large
7.	Primary vertical stiffness	Moderate	Small	Small
8.	Travel-primary vertical suspension	Small	Small	Small
9.	Lateral primary free play	Moderate	Small	Small
10.	Pedestal friction	Small	Small	Small
11.	Limiting force primary vertical dampers	Small	Small	Small

TABLE 1.2 - SUMMARY OF PARAMETER SENSITIVITY
(page 1 of 2)

* The parameter numbers correspond to Figures 1.1 through 1.21 repsectively.

Small ...... Δ L/V < 0.05

Moderate ... Δ L/V = 0.05 - 0.10

Large ...... Δ L/V > 0.10

PARAMETER		SENSITIVITY WHEEL L/V	WHEELSET L/V	TRUCK-SIDE L/V
12.	Lateral secondary stiffness	Moderate	Small	Moderate
13.	Travel-secondary lateral suspension	Small	Small	Moderate
14.	Limit force - external secondary lateral damper	Small	Moderate	Small
15.	Bolster yaw friction factor	Small	Small	Small
16.	Tractive effort	Small	Small	Small
17.	Curvature	Moderate	Small	Small
18.	Amplitude of track defects	Large	Large	Large
19.	Wavelength of track defects	Large	Large	Large
20.	Number of pulse of track defects	Small	Large	Moderate
21.	Type of defect			
	: crosslevel	Moderate	Small	Small
	: lateral alignment	Large	Large	Large
	: vertical alignment	Small	Small	Small

TABLE 1.2 - SUMMARY OF PARAMETER SENSITIVITY (CONTINUED)
(page 2 of 2)

- BASELINE CONDITIONS

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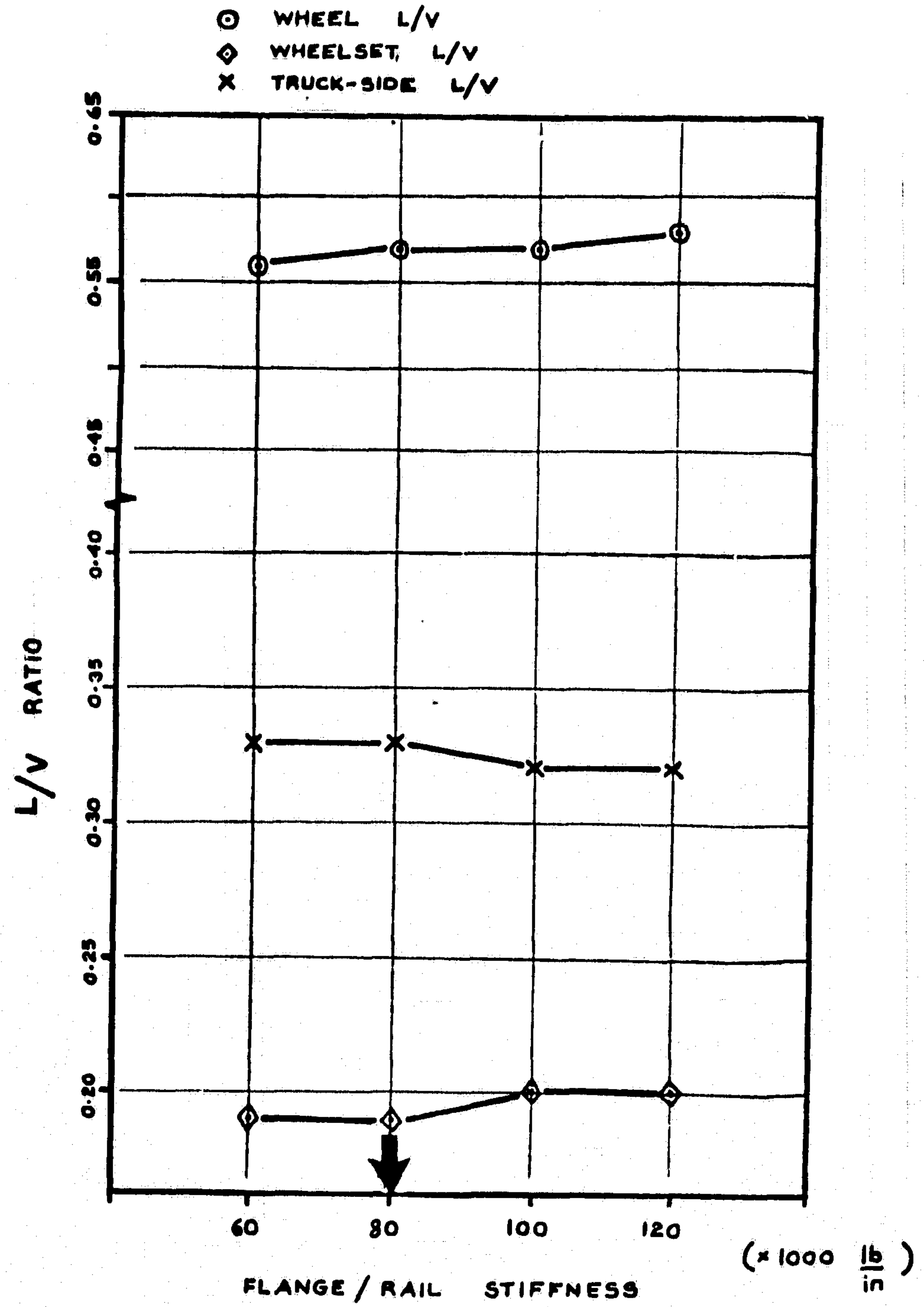

FIGURE 1.1 - COMPUTED SENSITIVITY TO FLANGE/ RAIL STIFFNESS

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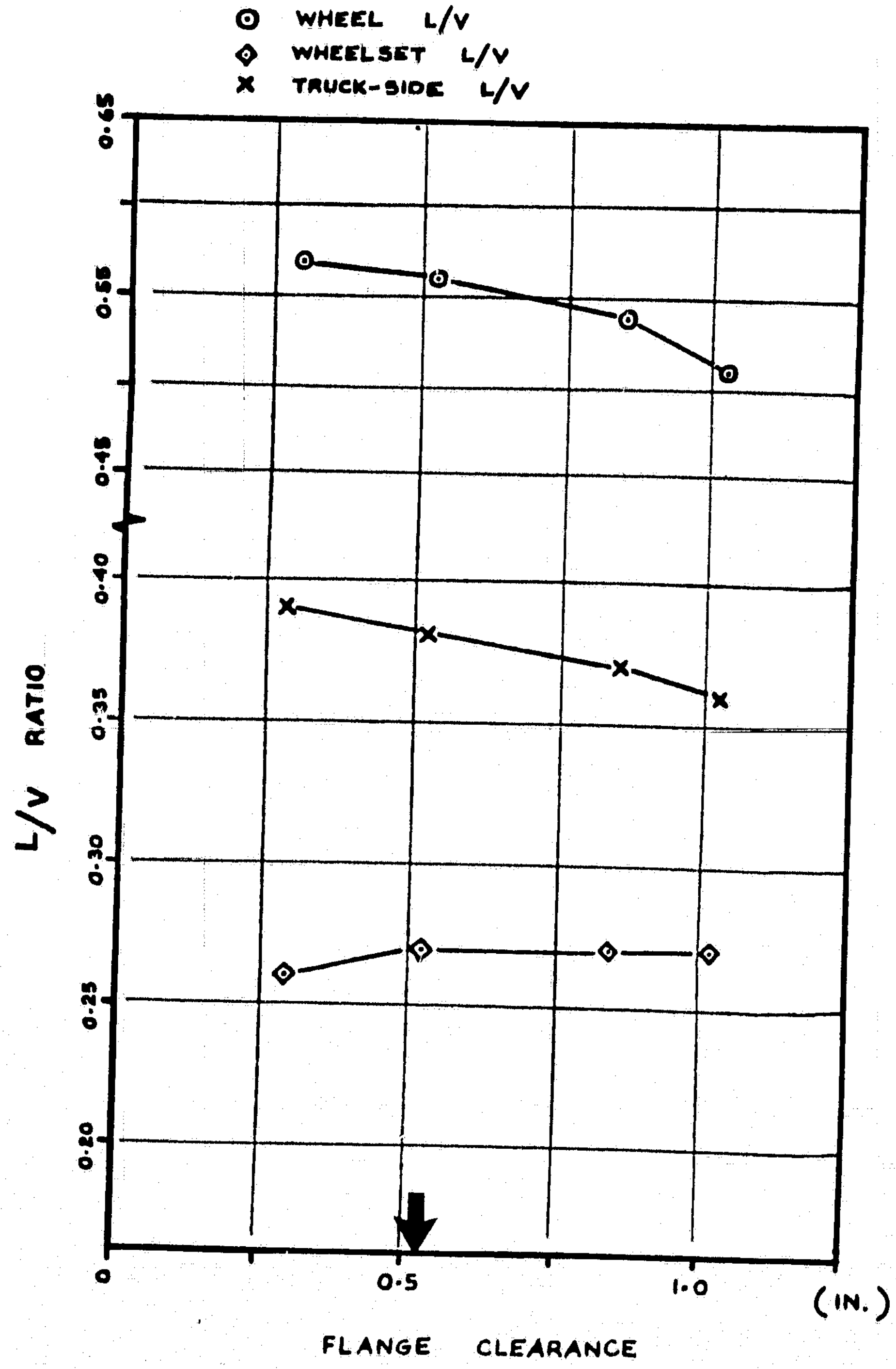

FIGURE 1.2 - COMPUTED SENSITIVITY TO FLANGE CLEARANCE

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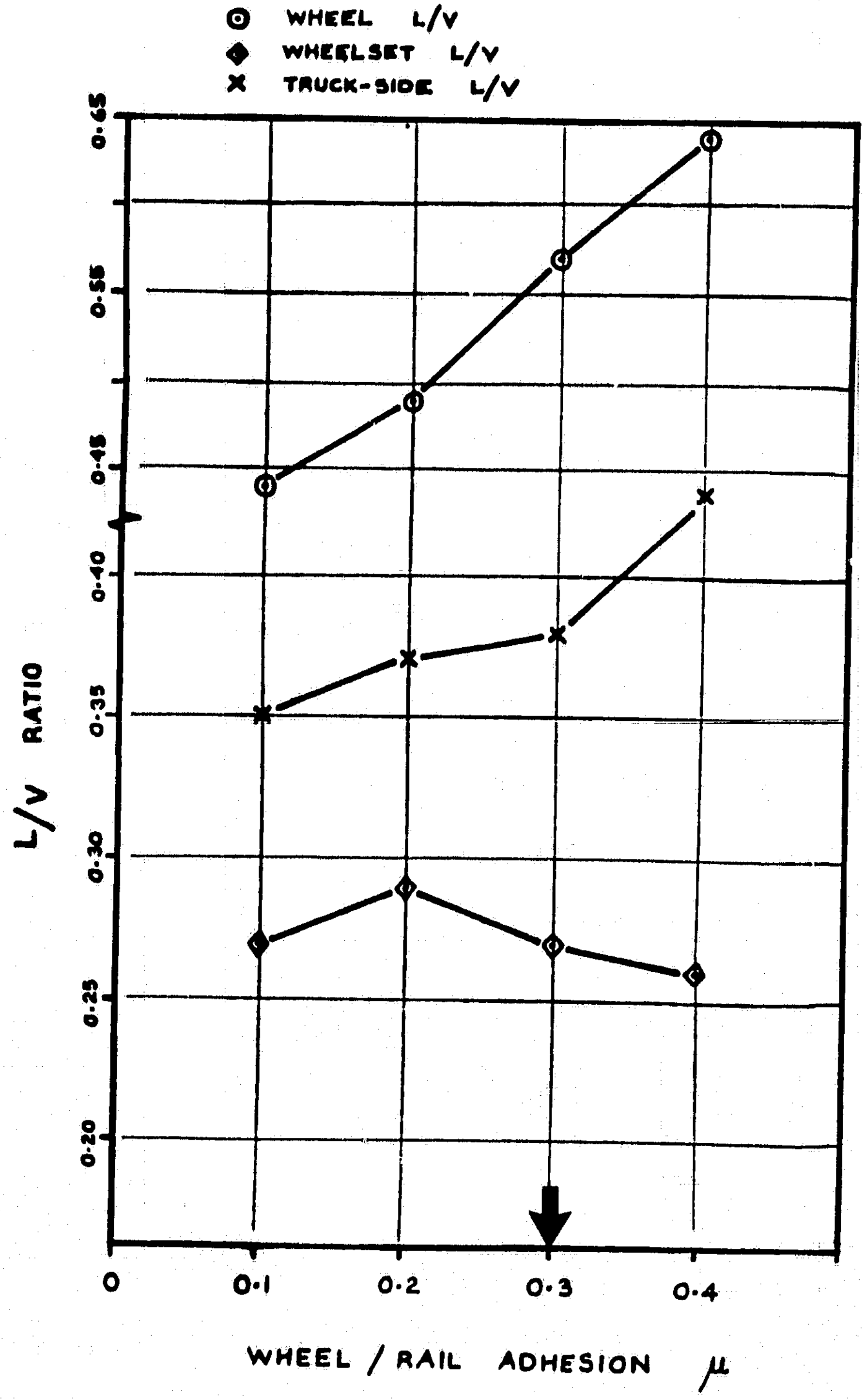

FIGURE 1.3 - COMPUTED SENSITIVITY TO WHEEL/RAIL ADHESION

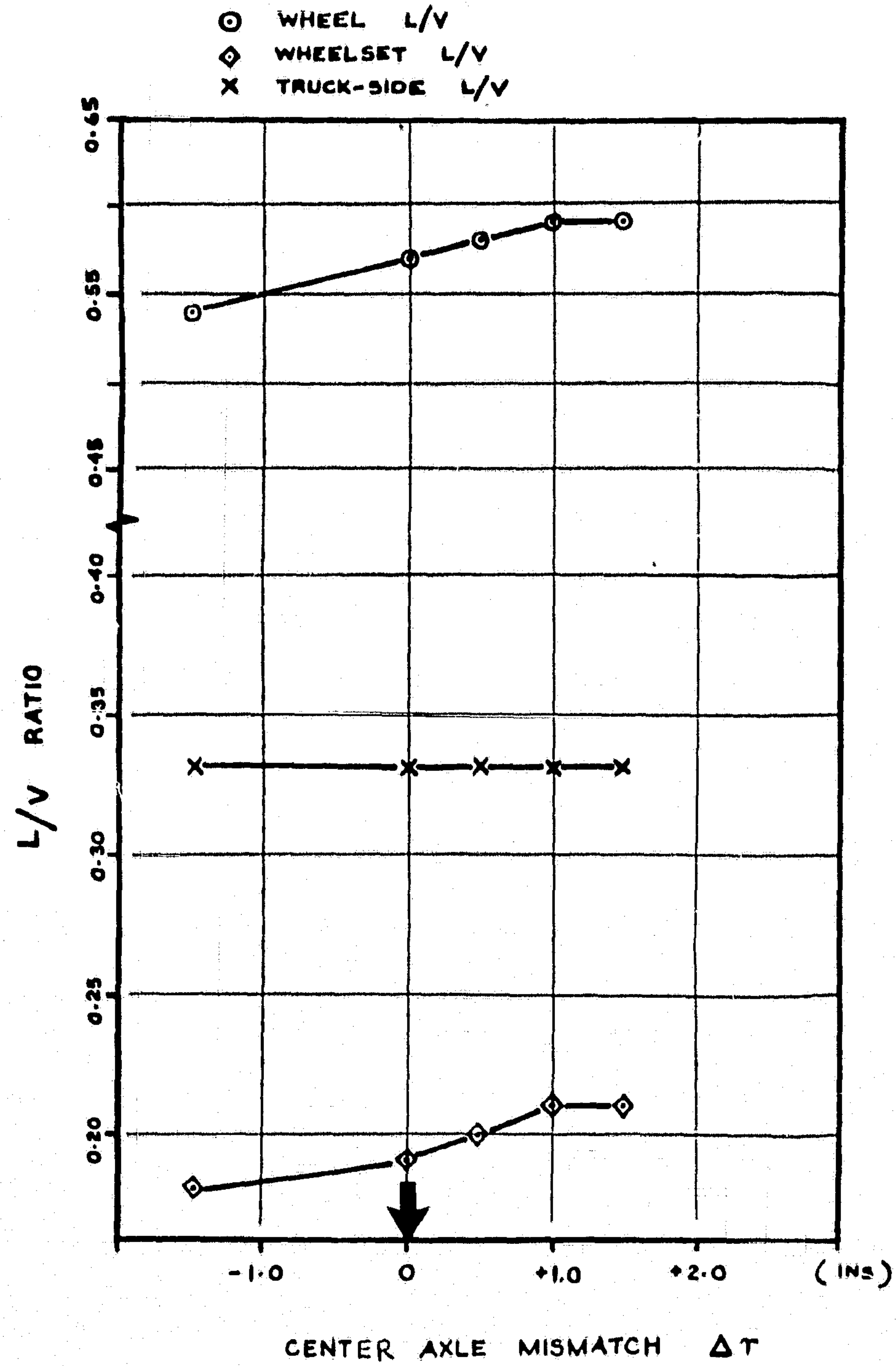

FIGURE 1.4 - COMPUTED SENSITIVITY TO CENTER AXLE MISMATCH

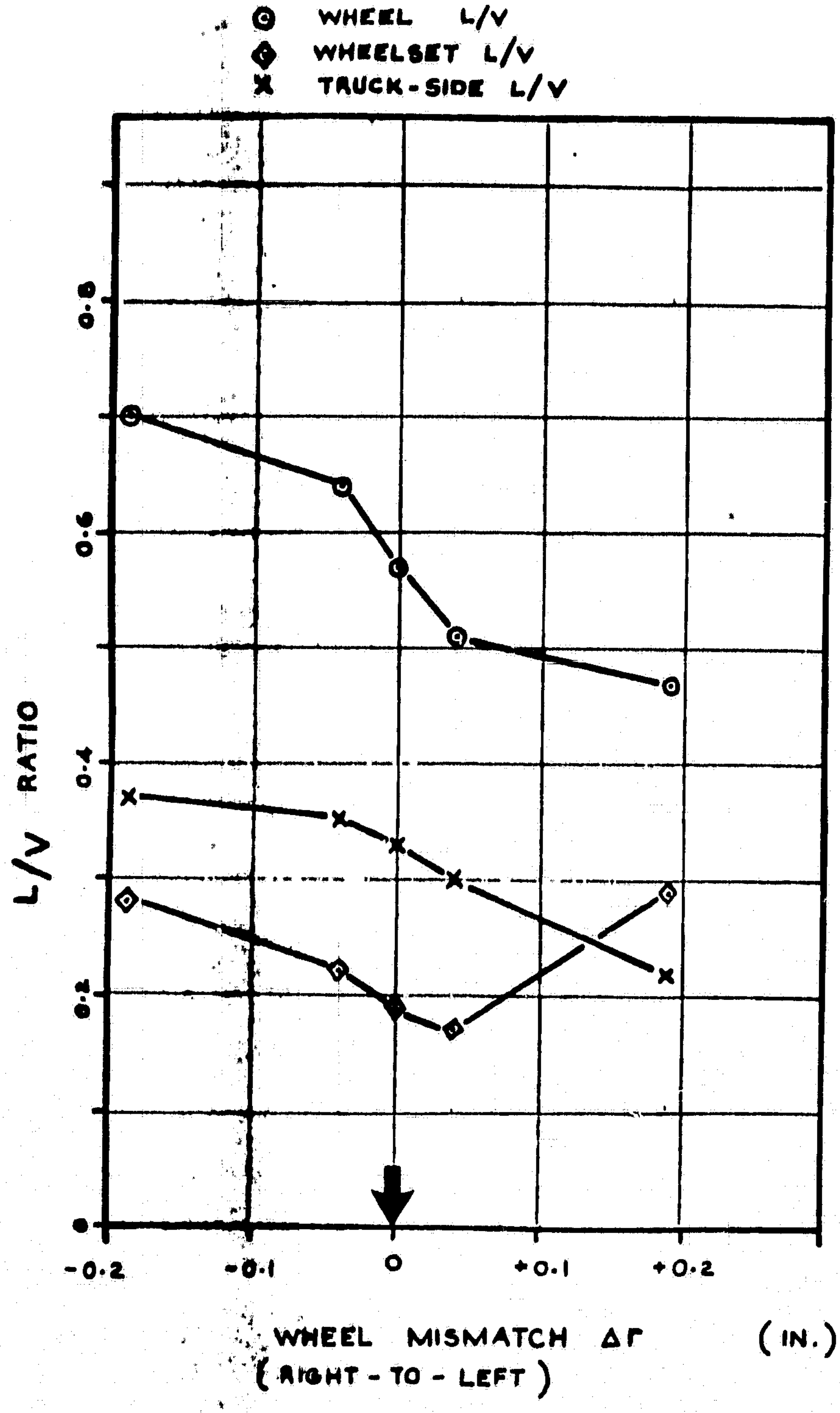

FIGURE 1.5 - COMPUTED SENSITIVITY TO WHEEL MISMATCH

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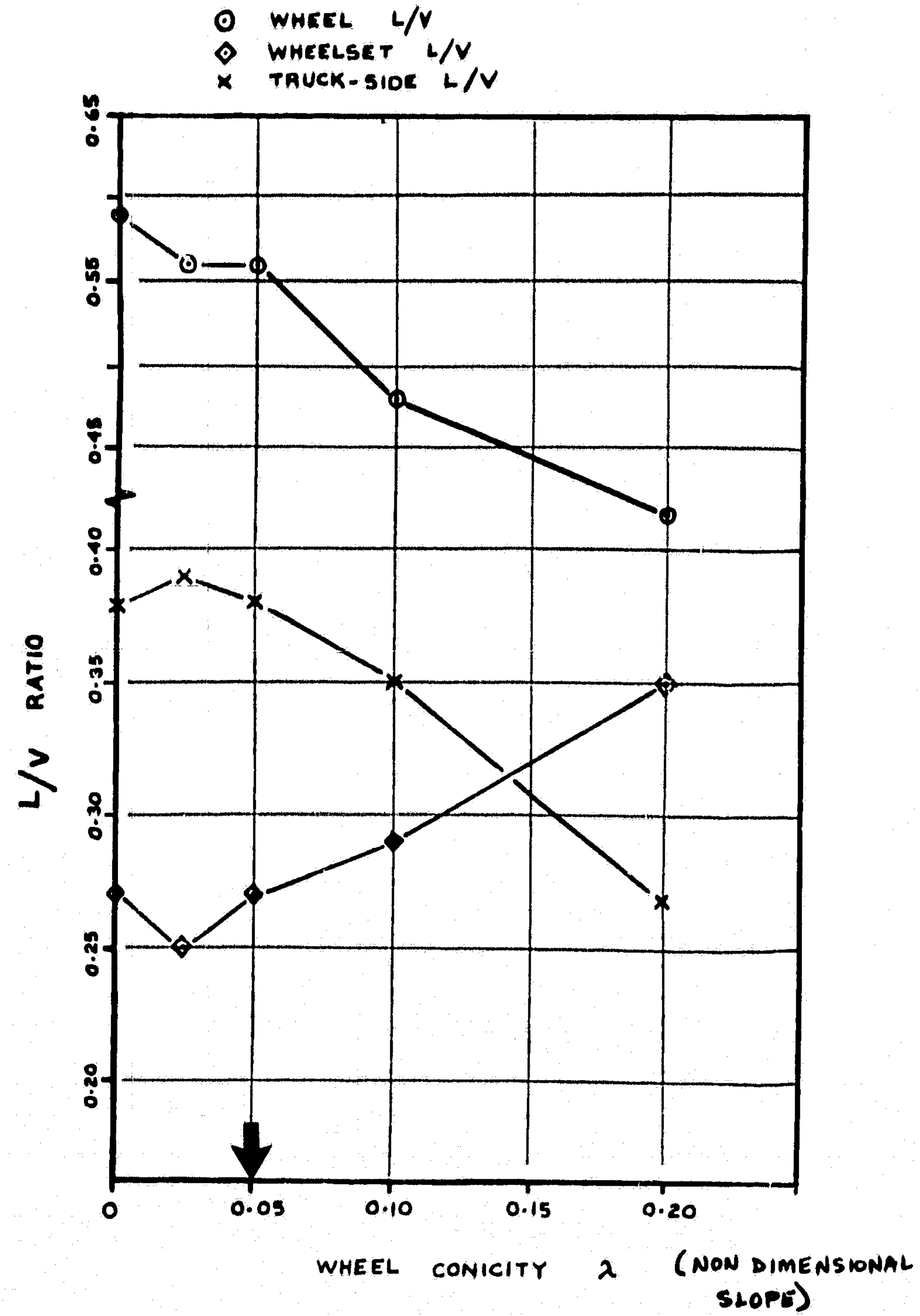

FIGURE 1.6 - COMPUTED SENSITIVITY TO WHEEL CONICITY

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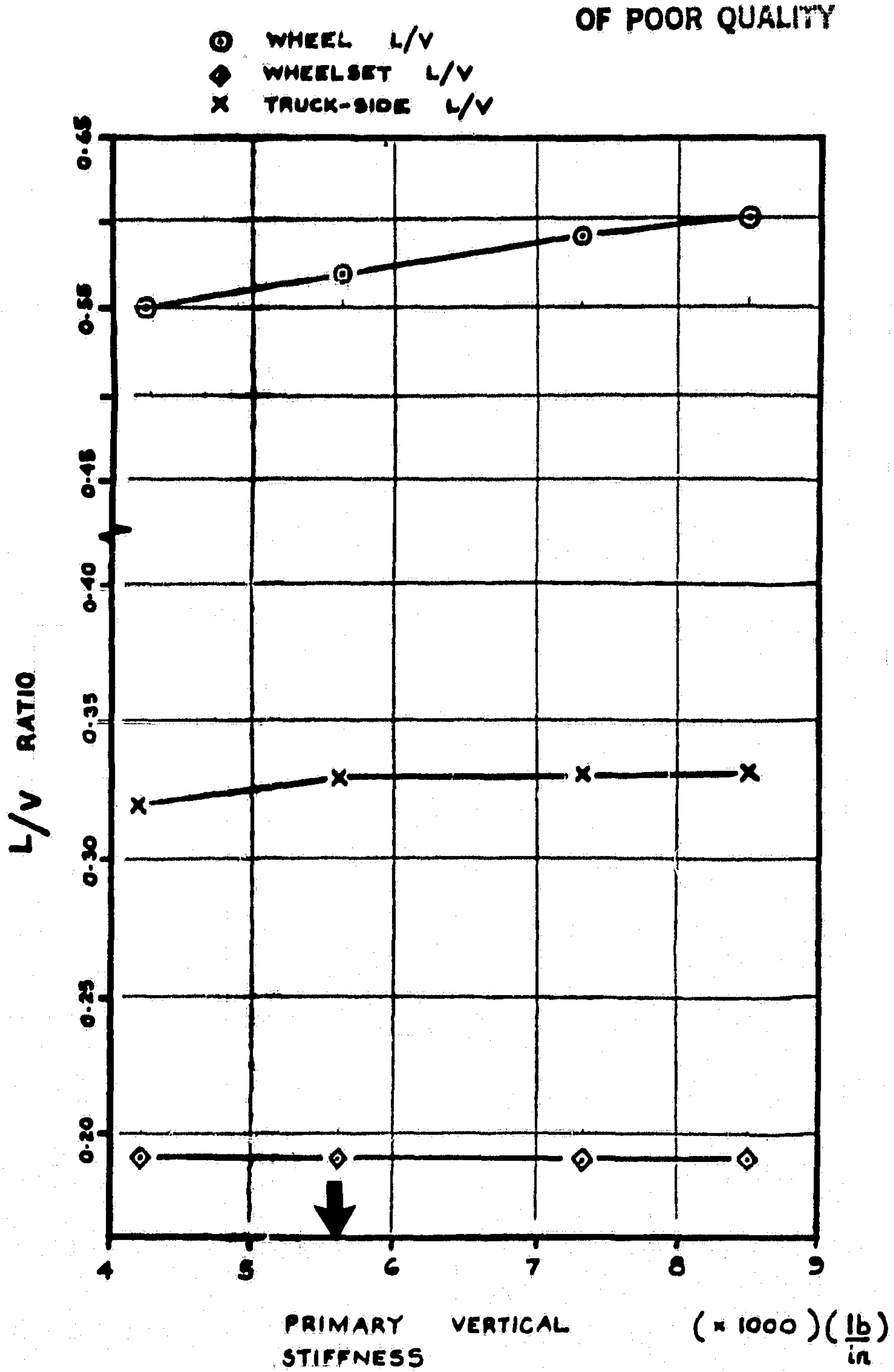

FIGURE 1.7 - COMPUTED SENSITIVITY TO PRIMARY VERTICAL STIFFNESS

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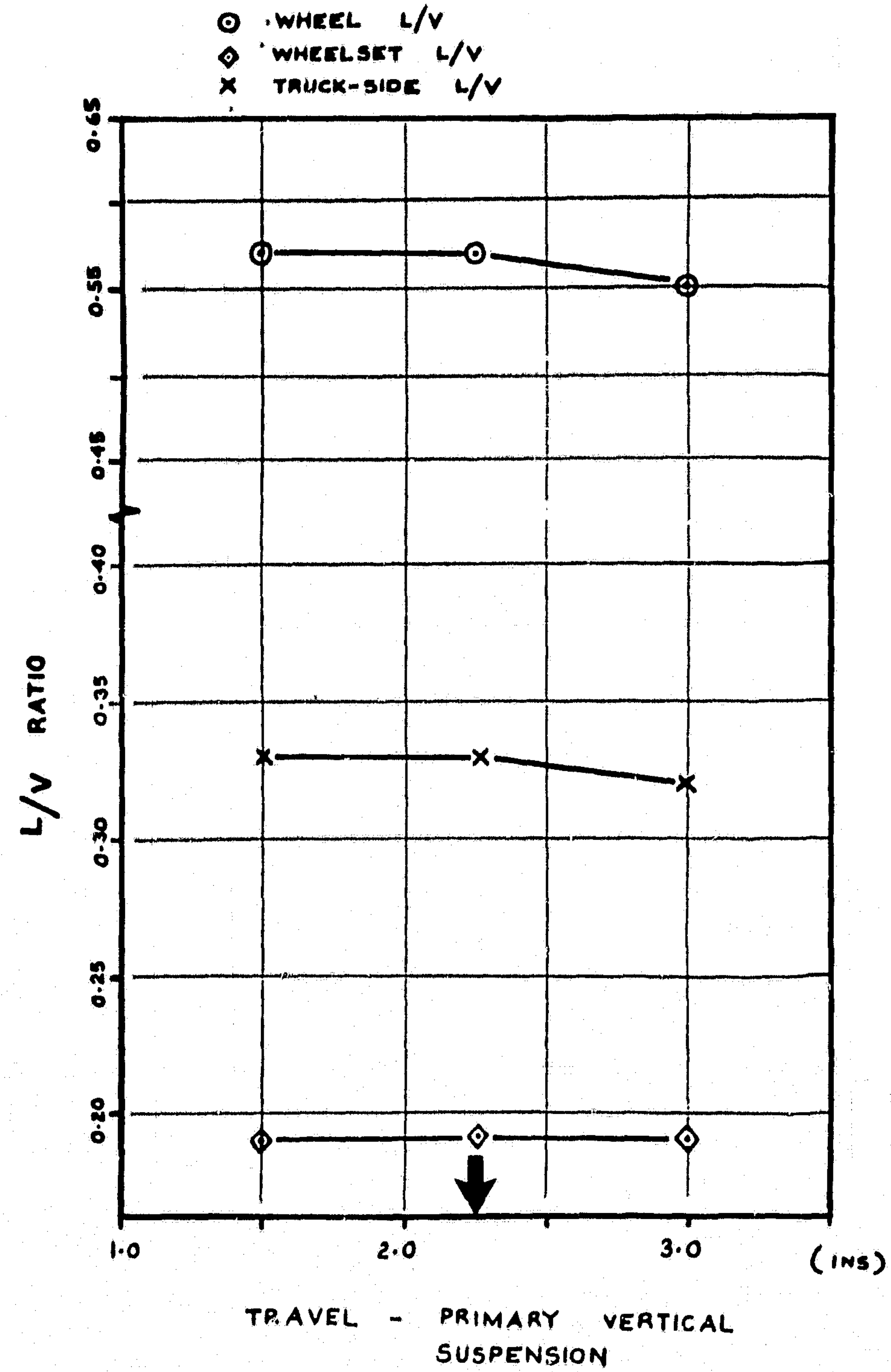

FIGURE 1.8 - COMPUTED SENSITIVITY TO TRAVEL - PRIMARY VERTICAL SUSPENSION

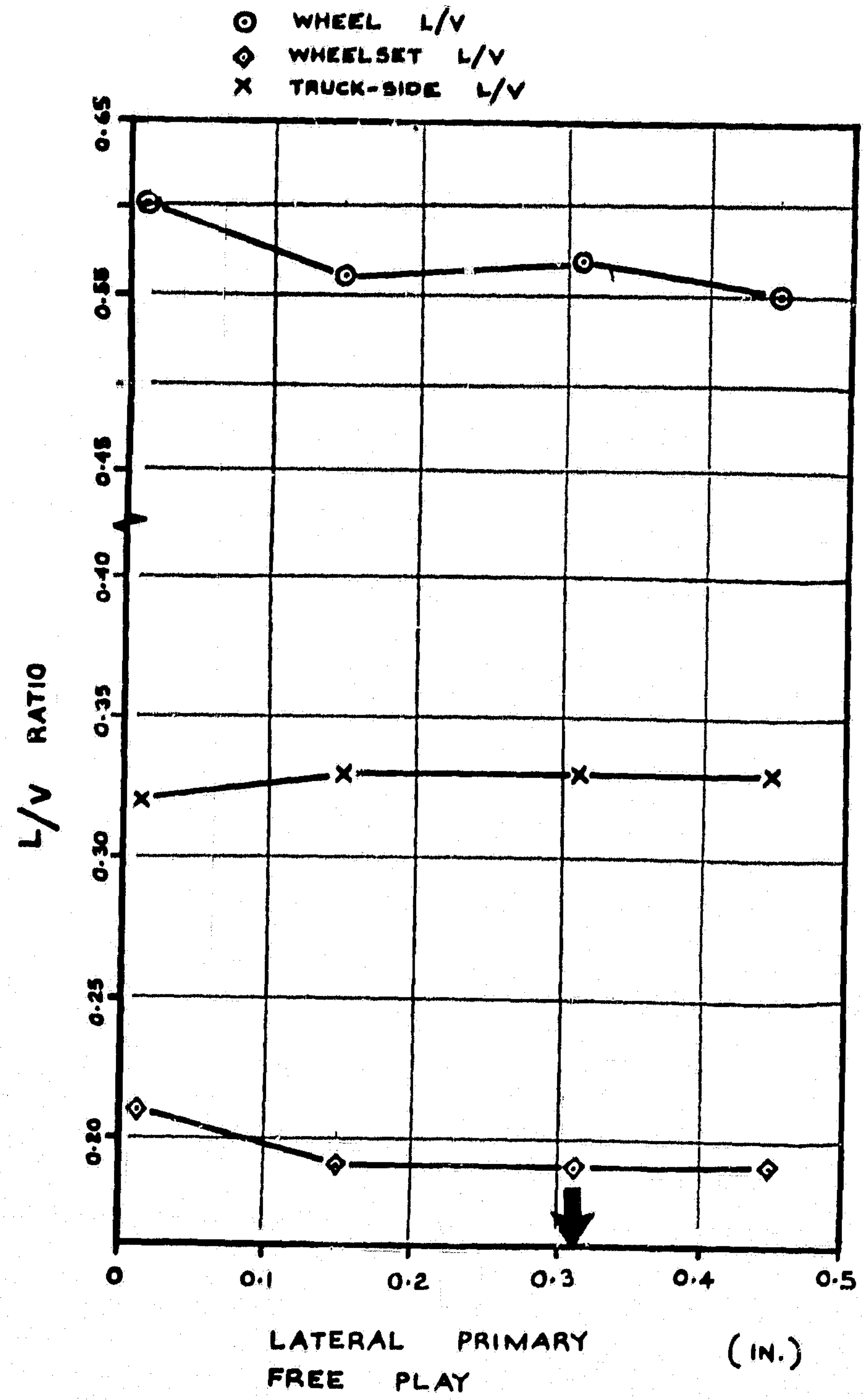

FIGURE 1.9 - COMPUTED SENSITIVITY TO LATERAL PRIMARY FREE PLAY

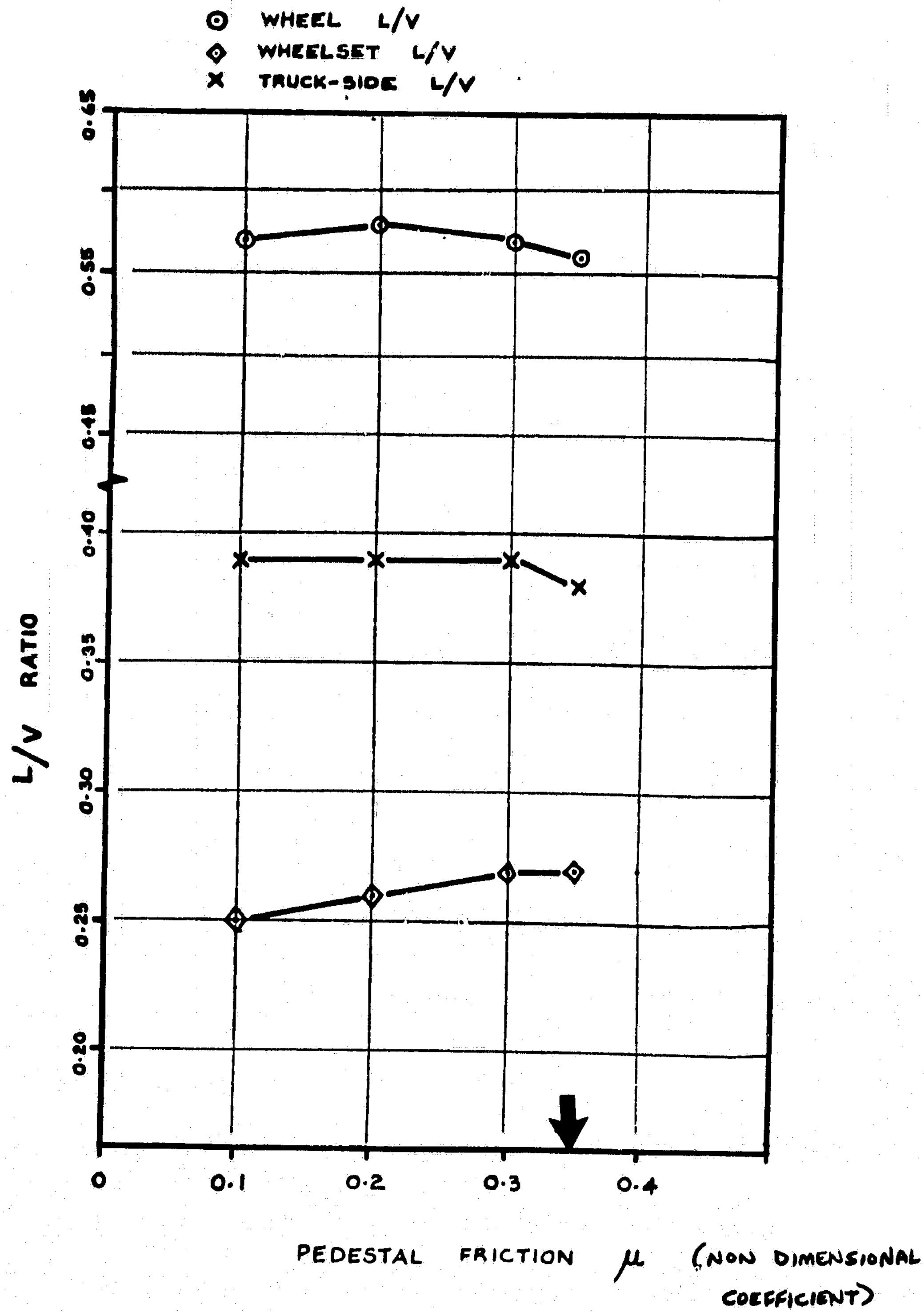

FIGURE 1.10 - COMPUTED SENSITIVITY TO PEDESTAL FRICTION

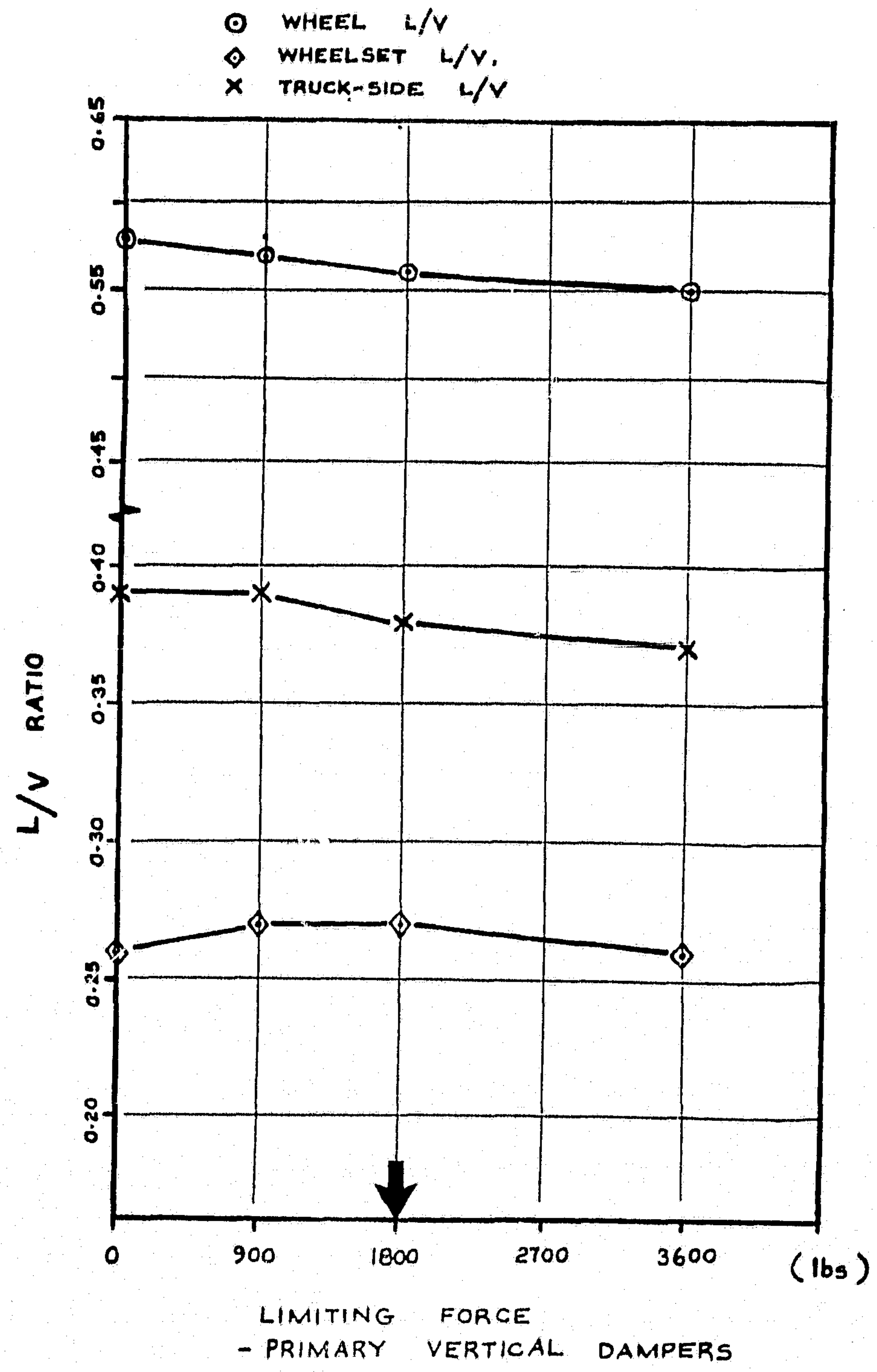

FIGURE 1.11 - COMPUTED SENSITIVITY TO LIMITING FORCE - PRIMARY VERTICAL DAMPERS

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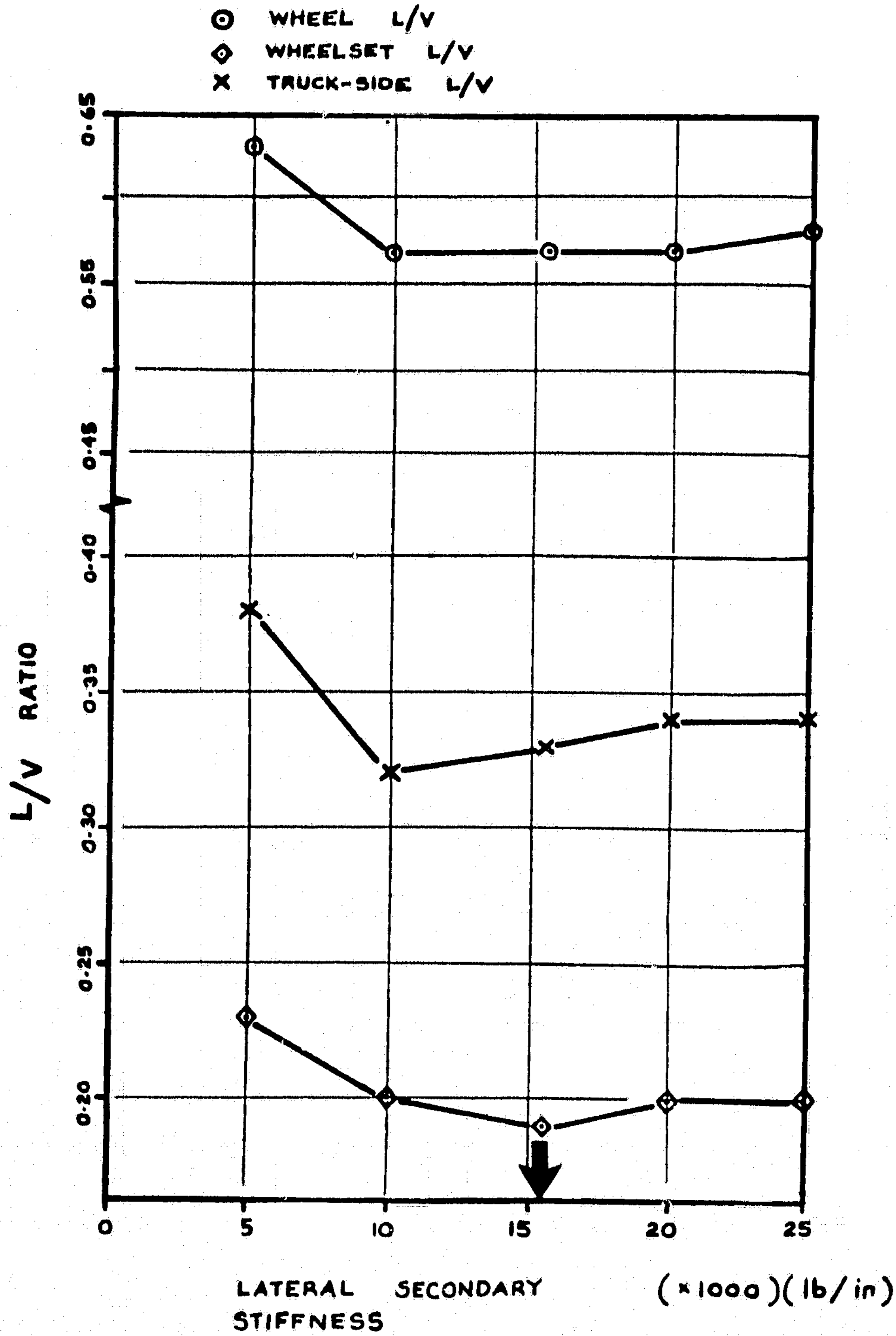

FIGURE 1.12 - COMPUTED SENSITIVITY TO LATERAL SECONDARY STIFFNESS

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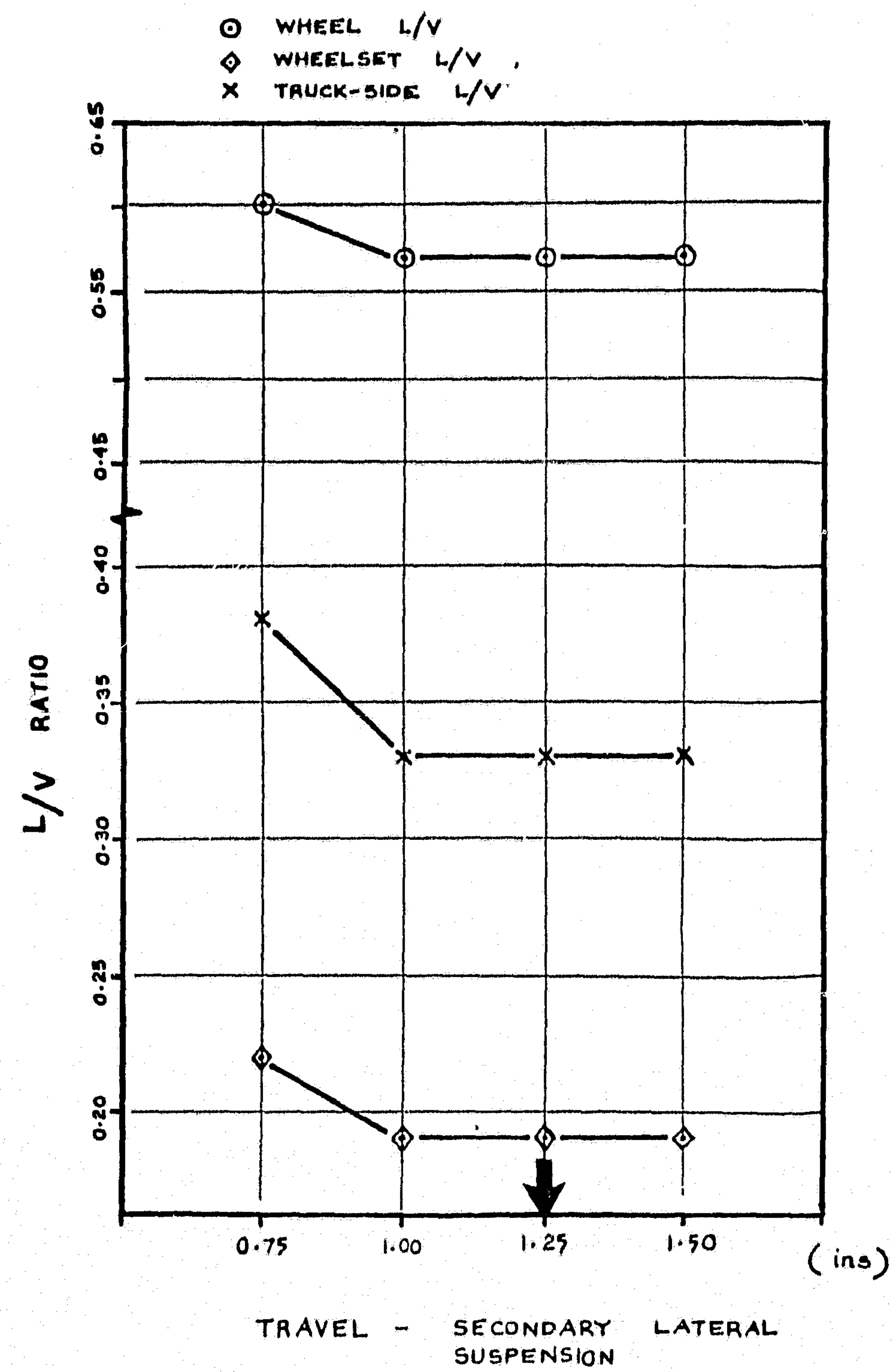

FIGURE 1.13 - COMPUTED SENSITIVITY TO TRAVEL - SECONDARY LATERAL SUSPENSION

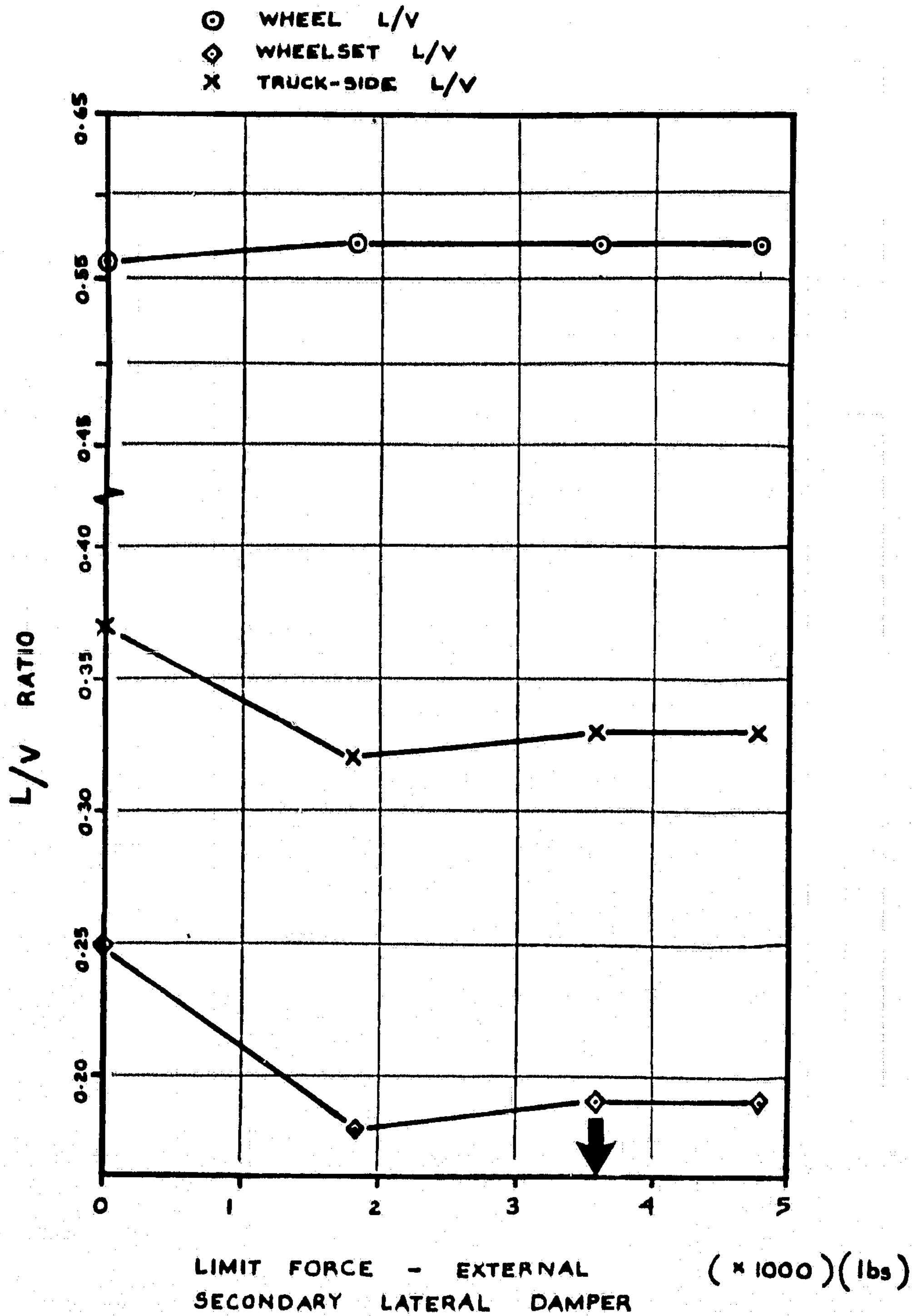

FIGURE 1.14 - COMPUTED SENSITIVITY TO LIMIT FORCE - EXTERNAL SECONDARY LATERAL DAMPER

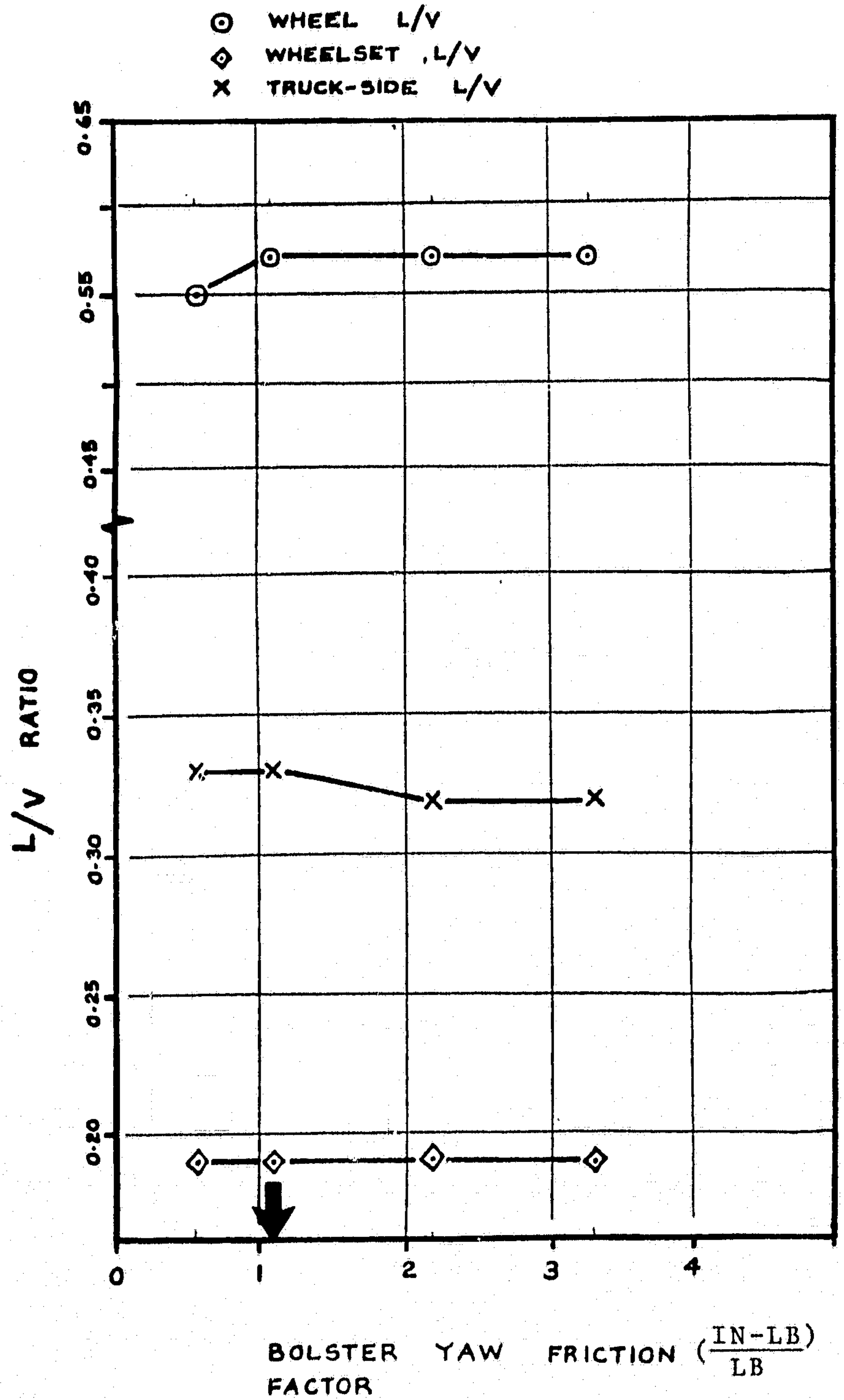

FIGURE 1.15 - COMPUTED SENSITIVITY TO BOLSTER YAW FRICTION FACTOR

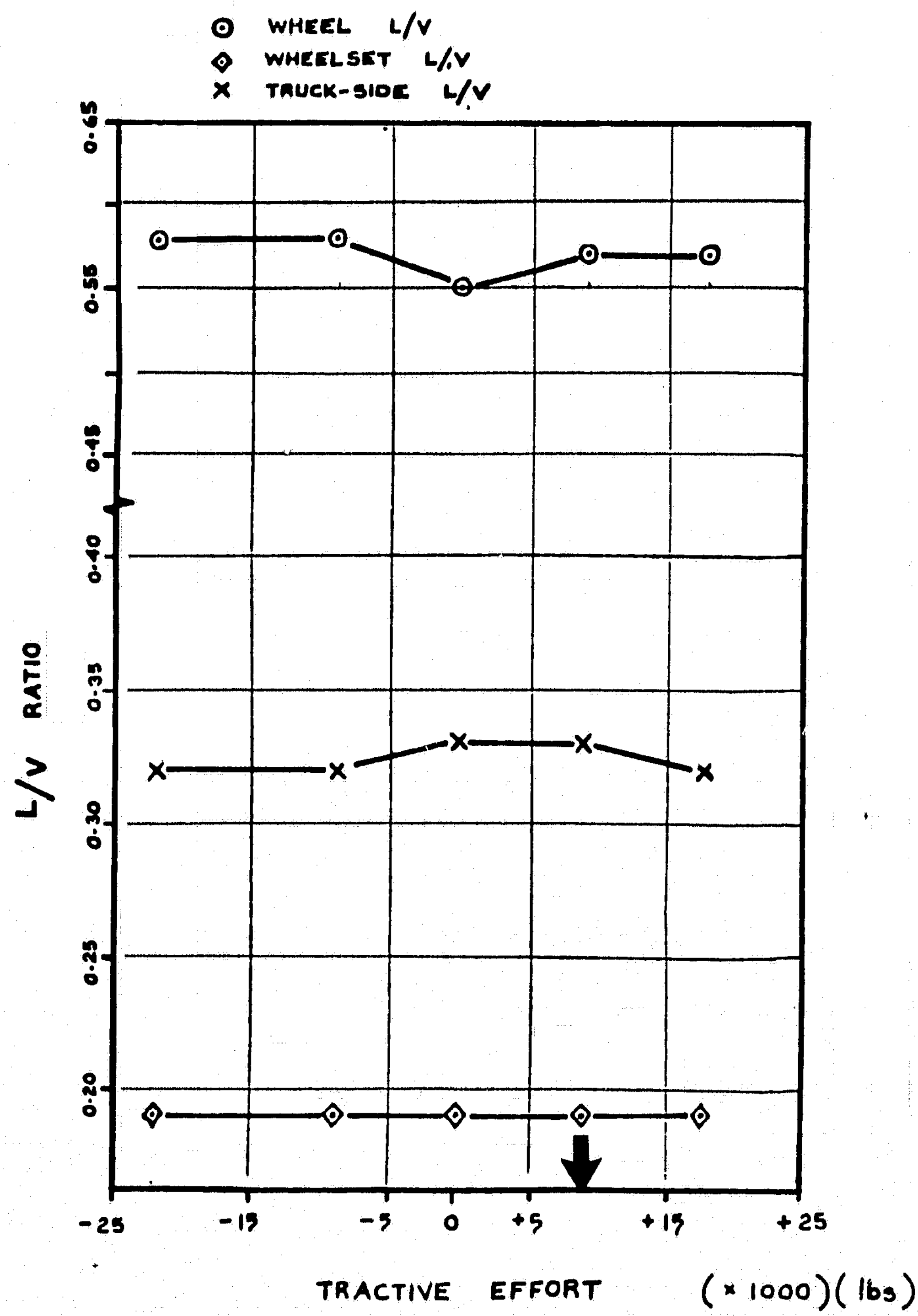

FIGURE 1.16 - COMPUTED SENSITIVITY TO TRACTIVE EFFORT

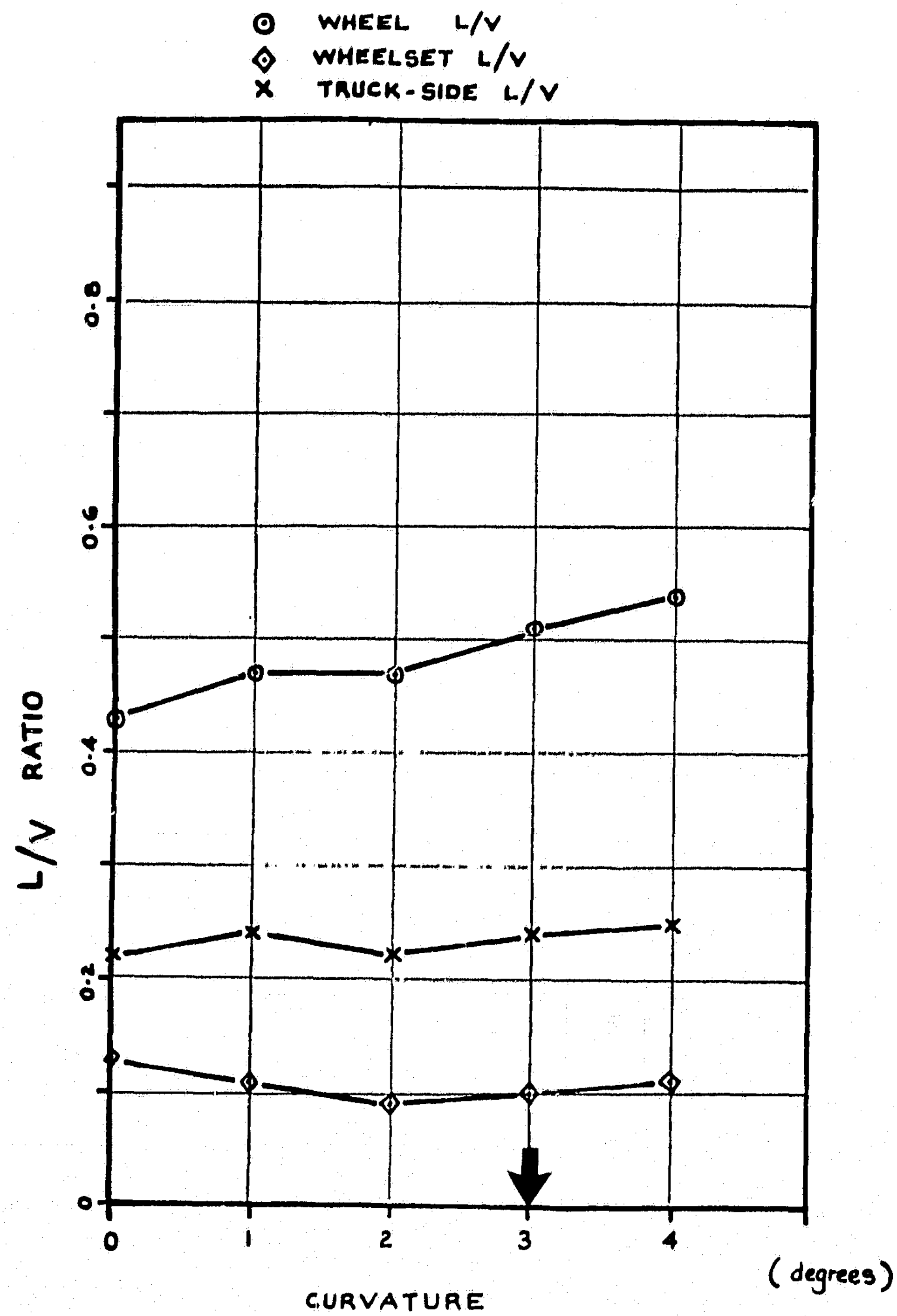

FIGURE 1.17 - COMPUTED SENSITIVITY TO CURVATURE

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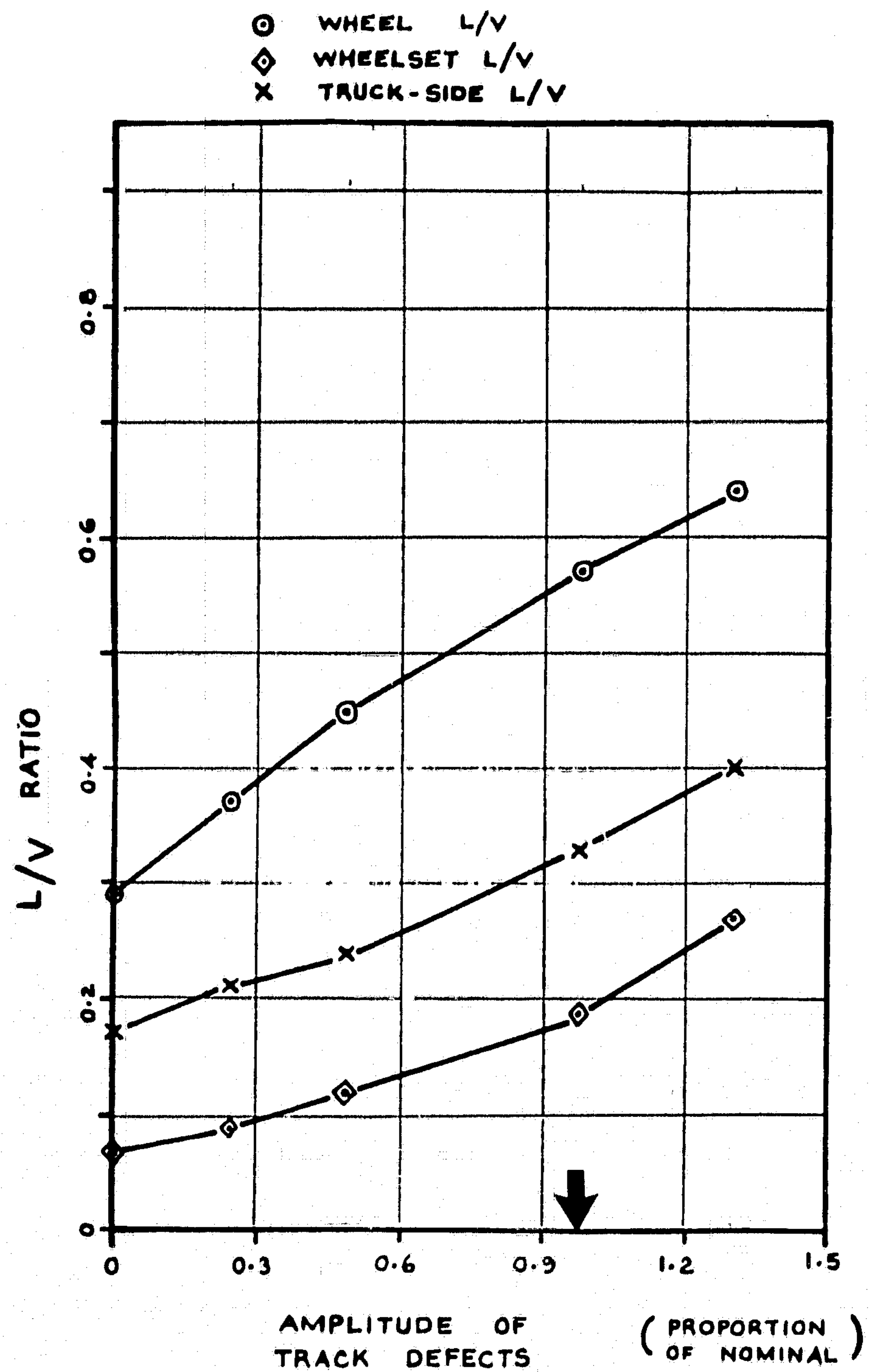

FIGURE 1.18 - COMPUTED SENSITIVITY TO AMPLITUDE OF TRACK DEFECTS

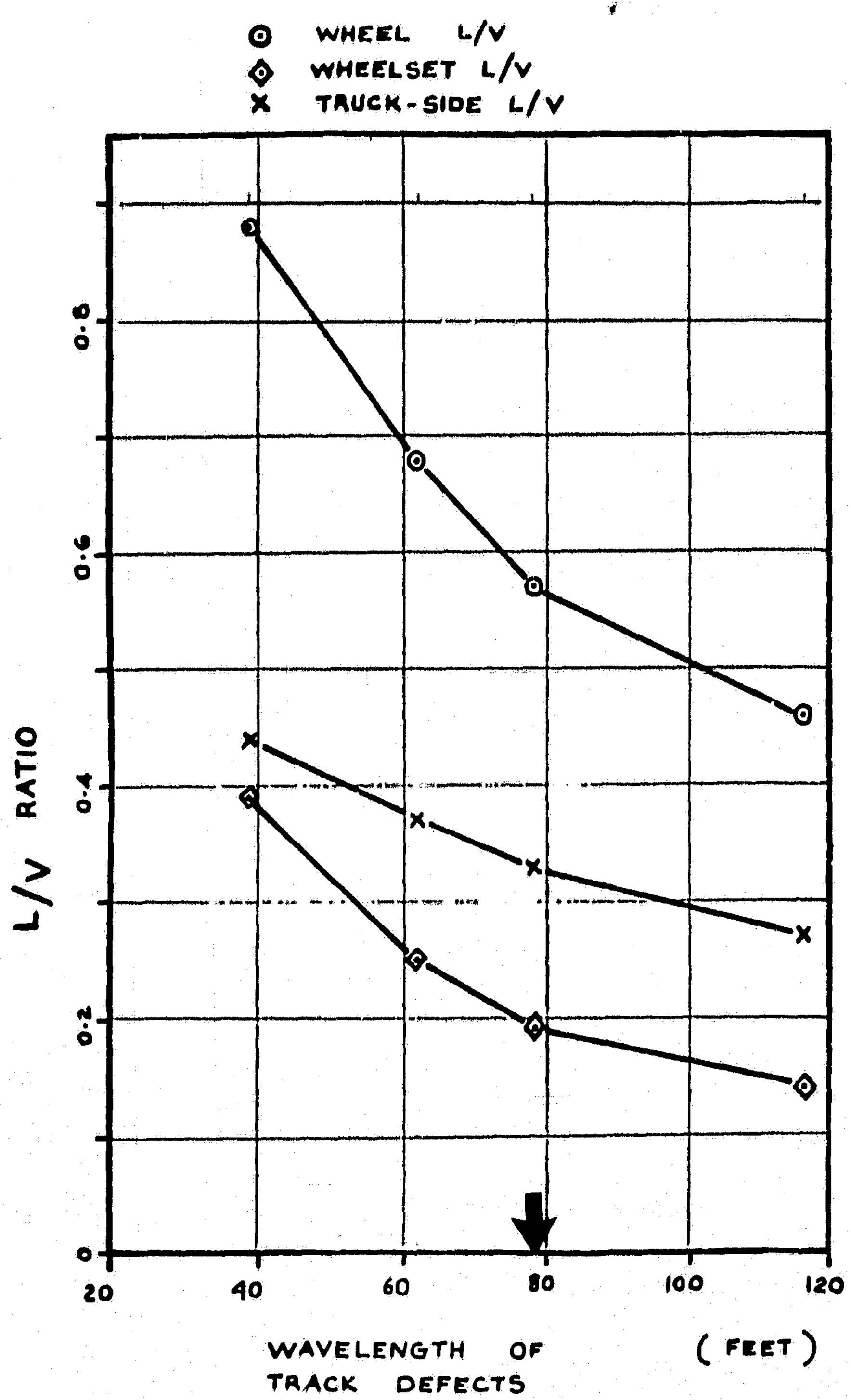

FIGURE 1.19 - COMPUTED SENSITIVITY TO WAVELENGTH OF TRACK DEFECTS

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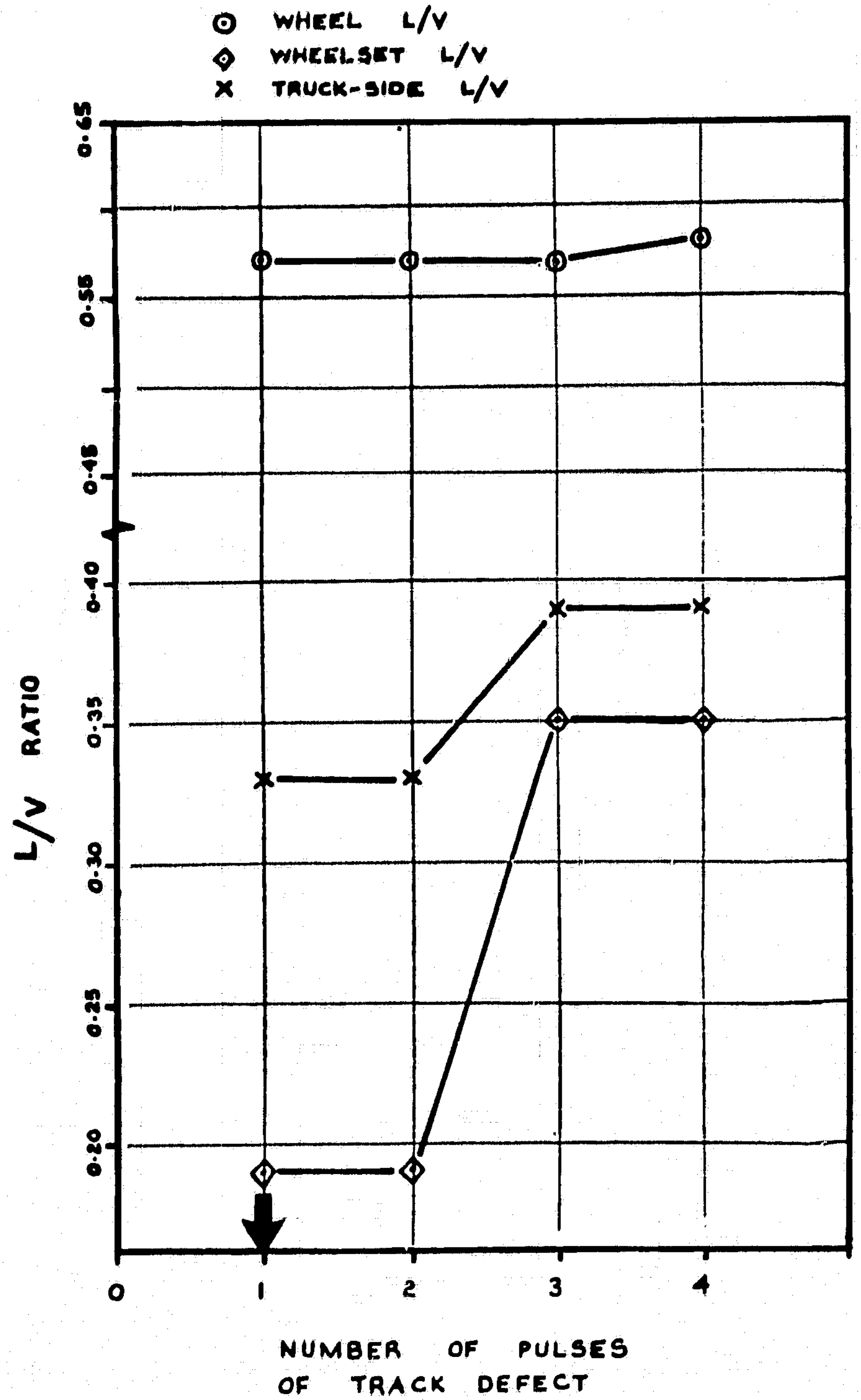

FIGURE 1.20 - COMPUTED SENSITIVITY TO NUMBER OF PULSES OF TRACK DEFECT

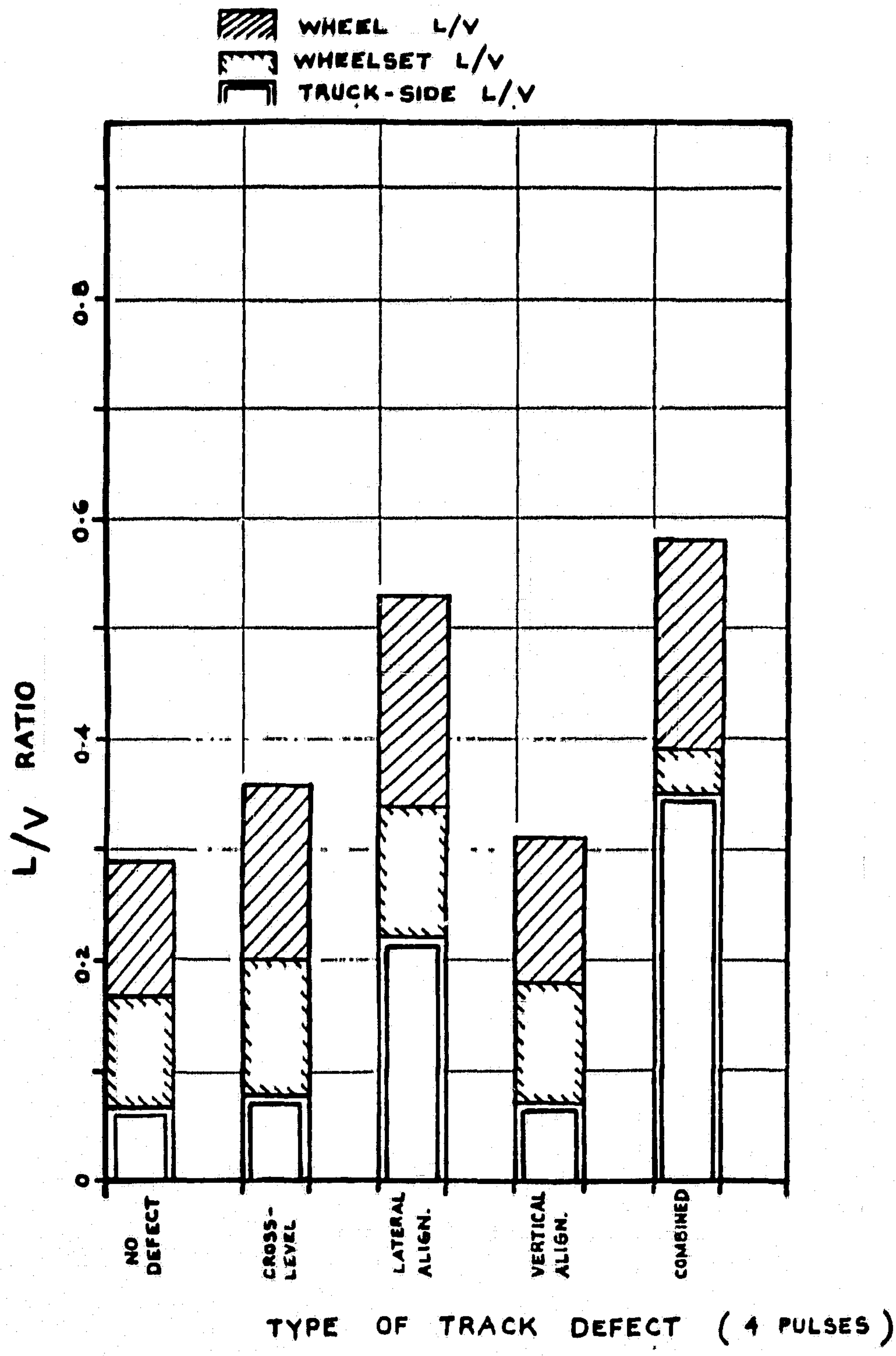

FIGURE 1.21 - COMPUTED SENSITIVITY TO TYPE OF TRACK DEFECT

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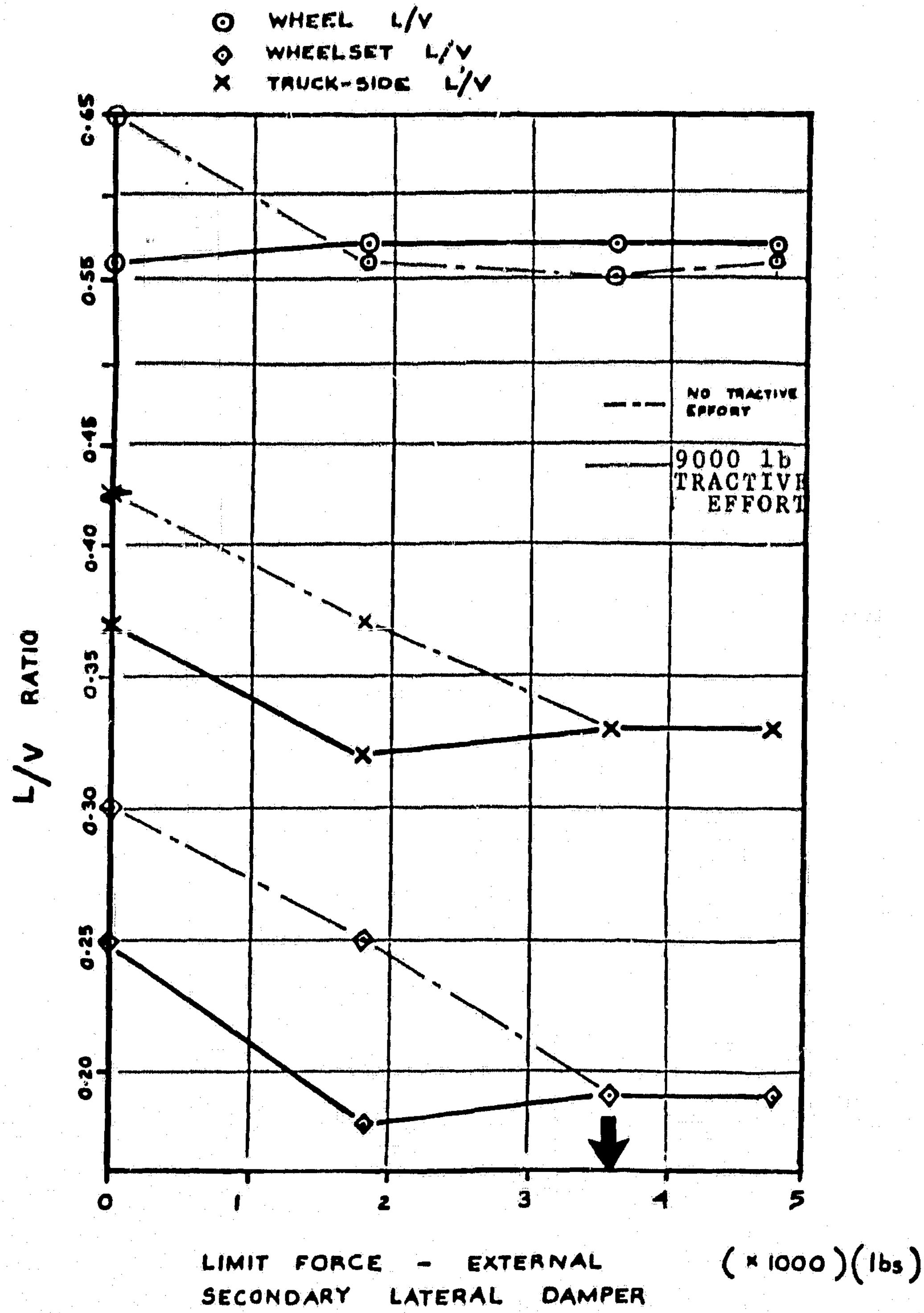

FIGURE 1.22 - COMPUTED SENSITIVITY TO LIMIT FORCE - EXTERNAL SECONDARY LATERAL DAMPER

Appendix 2 - Comparative Analysis

	Pg
2.1 Introduction	2-1
2.2 Definition of the Input Parameters	2-1
2.3 Comparative Analysis Results	2-3
2.4 Discussion	2-5

APPENDIX 2

COMPARATIVE ANALYSIS

2.1 INTRODUCTION

This section describes the selected input parameters, track geometry defects, and operating conditions used in the comparative analysis of the three following locomotives:

1. SDP-40F locomotive with new HTC trucks
2. U-30C locomotive
3. E-8 locomotive

The performance comparison is based on peak values of the three measures of safety, (i.e. wheel, wheelset, and truckside L/V ratios) when the locomotives are subjected to the same input functions.

2.2 DEFINITION OF THE INPUT PARAMETERS

2.2.1 Locomotive Parameters

The input parameters for each locomotive are grouped as follows:

1. Geometric Properties
2. Mass Properties
3. Suspension Properties

Table 2.1(a) gives a complete list of the Geometric Properties for all three locomotives.

Table 2.1(b) defines the Mass Properties of the locomotives and trucks.

The Input Parameters for the various suspension elements are defined in Table 2.1(c). Explanatory notes on some of the numerical values used are provided in Table 2.1(d).

2.2.2 Track Geometry Defects

A combination of crosslevel, lateral, and vertical misalignments having amplitudes equal to the maximum limits for FRA class 4 track safety standards are selected as track geometry defects. Two different cases are tested using the same defect amplitude, but with different wavelength. In the first case, the wavelength is chosen to be 78 ft (equal to the wavelength used in the Perturbed Track Test), and in the second case, 39 feet, which corresponds to the standard rail length. For both cases, each track defect is only used once (single pulse). Table 2.3 describes the details of each track geometry defect.

2.2.3 Operational Parameters

The operational parameters are selected as follows:

Track curvature is set at 3 degrees. This curvature has the advantage of satisfying the required range of track speeds for typical class 4 tracks. It also corresponds to the curvature over which many of the observed derailments occurred on six-axle locomotives.[2]

With 6 inches of superelevation, a maximum of 3 inches of superelevation deficiency, and using the procedure illustrated in Table 2.2, the minimum and maximum vehicle speeds were found to be 40 mph and 65 mph respectively.

In summary, the selected operational parameters are:

1. 3 degree curve, 6 inches superelevation.
2. Speed range: 40 to 65 mph
3. 9000 pounds tractive effort.

The same parameters are used for both combined defects and for all three locomotives.

2.3 COMPARATIVE ANALYSIS RESULTS

Results for all simulations are shown in Table 2.4(a) and (b), indicating peak values of the measures of safety and the position on the locomotive where the peak values occurred. Results of peak values are also displayed graphically in Figures 2.1 to 2.6.

2.3.1 Comparative Performance on the 78 ft Wavelength Defect

Considering "Wheel L/V", indicating flange climbing potential (Fig. 2.1), only minor differences exist between the three different locomotives. As well, since the peak wheel L/V ratios are lower than currently accepted critical values for derailment (typically above 0.8), it appears that the probability of derailment on the selected defect due to flange climbing is small.

In Figure 2.2, relatively large differences are seen between the locomotives when considering wheelset L/V, indicating the potential for track panel shift. At 65 mph the U-30C produces peak values nearly twice as high as the other two. It can be noted as well that this peak value occurs on the trailing axle of the trailing truck. A similar response is found on the U-30C when considering truck side L/V (Fig. 2.3).

2.3.2 Comparative Performance on the 39 ft Wavelength Defect

Peak wheel L/V ratios are not found to be significantly different on the three locomotives, the differences being in the 10 percent or less range (Fig. 2.4). The SDP-40F gave the lower values for all speeds. On wheelset L/V ratio (Fig. 2.5), the E-8 locomotive gives the higher values, but the difference is more pronounced at lower speeds than at 65 mph.

On truck side L/V ratio, the U-30C locomotive shows the best performance, contrary to what was shown previously for the 78 ft wavelength.

2.4 DISCUSSION

The largest and probably most significant difference in behaviour observed between the three locomotives is the one resulting from the long wavelength combined defect at 65 mph. In this particular case, the U-30C locomotive is found to produce significantly higher peak values of wheelset L/V and truck side L/V, as compared to the other two locomotives.

In order to provide an engineering explanation for this situation, the parameters of the U-30C are compared to those of the SDP-40F. The SDP-40F locomotive is chosen for reference because its weight and inertial characteristics are not significantly different to those of the U-30C. In this case, only the suspension characteristics can be responsible for such a large difference in behaviour.

If one examines only those suspension parameters which show differences of 50 percent or more, three parameters are found as follows:

1. Lateral secondary suspension dampers.
2. Primary vertical stiffness.
3. Pedestal friction.

In order to quantify the effect of those three parameters, additional runs were made with parameter modifications as shown in Table 2.5.

It is clear from the numerical results of Table 2.5 that the absence of lateral secondary damping in the U-30C locomotive is the explanation for its different behaviour as compared with the other two.

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INPUT PARAMETERS

DEFINITION		UNITS	SDP-40F	U-30C	E-8	NO.
GEOMETRIC PROPERTIES						
LOCOMOTIVE BODY						
COUPLER PIN/CG-LONG.		IN	404.000	372.000	403.000	1
SECONDARY/CG-VERT.		IN	50.200	43.100	44.500	2
PRIMARY/SECONDARY-VERT.		IN	7.500	14.000	14.500	3
COUPLER/RAIL-VERT.		IN	34.500	34.500	34.500	4
CENTER OF PRESSURE/RAIL-VERT.		IN	120.000	120.000	120.000	5
TRUCK CENTER/CG-LONG.		IN	276.000	245.500	258.000	6
TRUCK FRAMES						
HALF TRUCK WHEELBASE		IN	* 82.200	* 82.500	84.000	7
HALF LATERAL SPACING		IN	39.500	39.750	39.000	8
THICKNESS OF SHIMS	LEFT AXLE 1	IN	0.000	0.000	0.000	9
IN THE VERTICAL	2	IN	0.000	0.000	0.000	10
PRIMARY SUSPENSION	3	IN	0.000	0.000	0.000	11
	4	IN	0.000	0.000	0.000	12
(POSITIVE WHEN	5	IN	0.000	0.000	0.000	13
SHIMS ADDED)	6	IN	0.000	0.000	0.000	14
	RIGHT 1	IN	0.000	0.000	0.000	15
	2	IN	0.000	0.000	0.000	16
	3	IN	0.000	0.000	0.000	17
	4	IN	0.000	0.000	0.000	18
	5	IN	0.000	0.000	0.000	19
	6	IN	0.000	0.000	0.000	20
WHEELSET/TRACTION MOTOR ASSEMBLY						
NOMINAL TREAD RADIUS		IN	20.000	20.000	18.000	21
WHEEL TREAD CONICITY		IN	.050	.050	.050	22*
DIFFERENCE IN MEAN	AXLE 1	IN	0.00	0.00	0.00	23
ROLLING RADIUS FROM	2	IN	0.00	0.00	0.00	24
NOMINAL	3	IN	0.00	0.00	0.00	25
(POSITIVE WHEN LARGER	4	IN	0.00	0.00	0.00	26
THAN NOMINAL)	5	IN	0.00	0.00	0.00	27
	6	IN	0.00	0.00	0.00	28
MISMATCH IN WHEEL ROLLING	AXLE 1	IN	0.000	0.000	0.000	29
RADIUS FROM SIDE TO SIDE	2	IN	0.000	0.000	0.000	30
(POSITIVE WHEN WHEEL ON	3	IN	0.000	0.000	0.000	31
LEFT RAIL IS LARGER THAN	4	IN	0.000	0.000	0.000	32
THAT ON RIGHT RAIL)	5	IN	0.000	0.000	0.000	33
	6	IN	0.000	0.000	0.000	34
TRACK						
HALF KINEMATIC GAUGE		IN	29.75	29.75	29.75	35
RAILHEAD CROWN RADIUS		IN	10.00	10.00	10.00	36

* see notes table 2.1(d)

TABLE 2.1 - INPUT PARAMETERS

(a) GEOMETRIC PROPERTIES

DEFINITION		UNITS	SDP-40F	U-30C	E-8	NO.
MASS PROPERTIES						
LOCOMOTIVE BODY						
WEIGHT		LB	295700.	300700.	210800.	37
ROLL MOMENT OF INERTIA		LB-IN-SEC2	1510000.	1720000.	1070000.	38
PITCH MOMENT OF INERTIA		LB-IN-SEC2	35300000.	39600000.	25200000.	39
YAW MOMENT OF INERTIA		LB-IN-SEC2	35300000.	39600000.	25200000.	40
TRUCK FRAMES						
WEIGHT		LB	15440.	14510.	15440.	41
ROLL MOMENT OF INERTIA		LB-IN-SEC2	52655.	56000.	55000.	42
PITCH MOMENT OF INERTIA		LB-IN-SEC2	161400.	178000.	170000.	43
YAW MOMENT OF INERTIA		LB-IN-SEC2	161400.	178000.	170000.	44
WHEELSET/TRACTION MOTOR ASSEMBLY						
WEIGHT	AXLE 1	LB	13124.	11580.	11580.	45
	2	LB	13124.	11580.	* 3200.	46
	3	LB	13124.	11580.	11500.	47
	4	LB	13124.	11580.	11500.	48
	5	LB	13124.	11560.	3200.	49
	6	LB	13124.	11580.	11500.	50
ROLL MOMENT OF INERTIA	AXLE 1	LB-IN-SEC2	20000.	18750.	18000.	51
ABOUT CG	2	LB-IN-SEC2	20000.	18750.	* 7000.	52
	3	LB-IN-SEC2	20000.	18750.	18000.	53
	4	LB-IN-SEC2	20000.	18750.	16000.	54
	5	LB-IN-SEC2	20000.	18750.	* 7000.	55
	6	LB-IN-SEC2	20000.	18750.	18000.	56
OFFSET OF CG FROM	AXLE 1	IN	10.0	10.0	10.0	57
AXLE CENTERLINE	2	IN	10.0	10.0	0.0	58
	3	IN	10.0	10.0	-10.0	59
(POSITIVE WHEN MOTOR	4	IN	-10.0	-10.0	10.0	60
TRAILS AXLE)	5	IN	-10.0	-10.0	0.0	61
	6	IN	-10.0	-10.0	-10.0	62
YAW MOMENT OF INERTIA	AXLE 1	LB-IN-SEC2	16780.0	16500.0	16500.0	63
	2	LB-IN-SEC2	16780.0	16500.0	7000.0	64
	3	LB-IN-SEC2	16780.0	16500.0	16500.0	65
	4	LB-IN-SEC2	16780.0	16500.0	16500.0	66
	5	LB-IN-SEC2	16780.0	16500.0	7000.0	67
	6	LB-IN-SEC2	16780.0	16500.0	16500.0	68

* see notes table 2.1(d)

TABLE 2.1 (CONTINUED)

(b) MASS PROPERTIES

DEFINITION	UNITS	SDP-40F	U-30C	E-8	NO.
SUSPENSION PROPERTIES					
SECONDARY					
LATERAL					
STIFFNESS					
RUBBER STIFFNESS	LB/IN	15500.	12000.	* 5000.	69
SPRING TRAVEL TO STOP(EACH SIDE)	IN	1.250	1.500	2.250	70
STIFFNESS BEYOND STOP	LB/IN	150000.	150000.	150000.	*71
DAMPING					
VISCOUS COEFFICIENT (RUBBER)	LB/(IN/SEC)	* 136.	* 65.	* 0.	72
FRICTION BOLSTER COEFFICIENT	--	.40	.45	.33	73
LVB COEFFICIENT FOR BOLSTER FRICTION	LB/(IN/SEC)	4000.	4000.	4000.	74
YAW DAMPING					
ROTATIONAL FRICTION FACTOR	IN-LB/LB	1.10	1.10	1.10	75
LVB COEFFICENT	IN-SEC	10000000.	10000000.	10000000.	76
EXTERNAL DAMPERS					
VISCOUS COEFFICIENT	LB/(IN/SEC)	1020.	0.	* 4000.	77
LIMITING FORCE	LB	3600.	0.	* 3000.	78
PRIMARY					
LATERAL					
STIFFNESS					
ROLLER BEARING FREE PLAY	IN	.31	.31	.31	79
RUBBER ELEMENTS TRAVEL	IN	.25	.25	.25	80
RUBBER PRELOAD	LB	1500.	1500.	1500.	81
STIFFNESS BEYOND STOP	IN	100000.	100000.	100000.	*82
DAMPING					
FRICTION FOR ROLLER BEARING	--	.10	.10	.10	83
LVB COEFFICIENT FOR FRICTION	LB/(IN/SEC)	4000.	4000.	4000.	84
VERTICAL					
STIFFNESS					
AVAILABLE TRAVEL(COMPRESSION)	IN	2.25	2.25	2.25	85
AVAILABLE TRAVEL(EXTENSION)	IN	2.25	2.25	2.25	86
SPRING STIFFNESS(PER JOURNAL)	LB/IN	5630.	7920.	*4900.	87
STIFFNESS BEYOND STOP(EITHER WAY)	LB/IN	200000.	200000.	200000.	*88
PEDESTAL DAMPING					
FRICTION COEFFICIENT(PEDESTAL FACE)	--	.35	.16	* 0.00	89
FRICTION COEFFICIENT(SIDE LUG)	--	.35	.16	* 0.00	90
LVB COEFFICIENT FOR TOTAL FRICTION	LB/(IN/SEC)	3000.	3000.	0.	91
EXTERNAL DAMPERS (OPTIONAL)					
CODE TO INDICATE THE PRESENCE OR ABSENCE OF EXTERNAL DAMPERS (0=NO DAMPER) (1=DAMPER) — LEFT AXLE 1	--	0.	1.	* 1.	92
2	--	1.	0.	1.	93
3	--	0.	1.	1.	94
4	--	0.	1.	1.	95
5	--	1.	0.	1.	96
6	--	0.	1.	1.	97
RIGHT 1	--	0.	1.	1.	98
2	--	1.	0.	1.	99
3	--	0.	1.	1.	100
4	--	0.	1.	1.	101
5	--	1.	0.	1.	102
6	--	0.	1.	1.	103
VISCOUS COEFFICIENT (COMPRESSION)	LB/(IN/SEC)	510.	3000.	3000.	104
VISCOUS COEFFICIENT(EXTENSION)	LB/(IN/SEC)	510.	3000.	3000.	105
LIMITING FORCE(COMPRESSION)	LB	1800.	1000.	1500.	106
LIMITING FORCE(EXTENSION)	LB	1800.	1000.	1500.	107
WHEEL/RAIL					
FLANGE					
FLANGEWAY CLEARANCE(EACH SIDE)	IN	.550	.550	.550	108
STIFFNESS AFTER FLANGE CONTACT	LB/IN	80000.	80000.	80000.	109
TREAD					
CREEP COEFFICIENT ADJUSTMENT FACTOR	--	.70	.70	.70	110
COULOMB FRICTION COEFFICIENT	--	.30	.30	.30	111

* see notes table 2.1(d)

TABLE 2.1 (CONTINUED)

(c) SUSPENSION PROPERTIES

TABLE 2.1 (CONTINUED)

(d) NOTES ON LOCOMOTIVE PARAMETERS

Parameter No.	Remarks
7	Axles assumed equally spaced for U-30C and SDP-40F.
22	Standard AAR wheel profile.
46	Estimated, without traction motor.
52-55	Estimated.
69	Equivalent to theoretical stiffness of swing hangers (ref. 14, main report).
71	Estimated.
72	Equivalent viscous coefficient at 2.5 Hz, based on test data at 0.25 Hz. For the E-8 locomotive see 77-78 below.
77-78	Secondary lateral friction damping, independent of tractive effort as per test data.
87	Equivalent to series-connected primary and secondary spring stiffness.
89-90	Test data indicates pedestal friction independent of tractive effort (see 92 to 107 below).
92 to 107	Equivalent to measured test data.

TABLE 2.2 - SUPERELEVATION PARAMETERS

Curve Parameters: 3 degrees
6" superelevation

Formula:

$$\underset{\text{(Required)}}{\text{Superelevation}} = 0.0007\ D\ V^2$$

D - degree of track curvature per 100 ft chord

V - speed (m.p.h.)

$$\underset{\text{(Deficiency)}}{\text{Superelevation}} = \underset{\text{(Required)}}{\text{superelevation}} - \underset{\text{(Actual)}}{\text{superelevation}}$$

SPEED (mph)	REQUIRED SUPERELEVATION (in)	ACTUAL SUPERELEVATION (in)	SUPERELEVATION DEFICIENCY (in)
40	3.36	6	-2.64
45	4.25	6	-1.75
50	5.25	6	-.75
55	6.35	6	.35
60	7.56	6	1.56
65	8.87	6	2.87

TABLE 2.3 - TRACK GEOMETRY DEFECT CHARACTERISTICS

DEFECT No. 1

COMPONENT	TYPE	AMPLITUDE* (in)	WAVELENGTH (ft)
1	CROSS-LEVEL	-1.25	78
2	LATERAL	1.5	78
3	VERTICAL	-1.375	78

DEFECT No. 2

COMPONENT	TYPE	AMPLITUDE* (in)	WAVELENGTH (ft)
1	CROSS-LEVEL	-1.25	39
2	LATERAL	1.5	39
3	VERTICAL	-1.375	39

* Note: The following gives an equivalent description of the composite track geometry defect, in terms of the individual rails.

Vertical, outer rail - 2 inches down,
Vertical, inner rail - 3/4 inch down,
Lateral, both rails - 1½ inch to outside of curve.

TABLE 2.4 - COMPARATIVE ANALYSIS RESULTS

(a) 78 ft Wavelength Geometry Defect

LOCOMOTIVE	SPEED (mph)	PEAK VALUES OF SAFETY INDICATORS		
		Wheel L/V	Wheelset L/V	Truck Side L/V
SDP-40F	40	.51(L1,L4)	.15(R2,R5)	.18(R1,L1,R2)
	45	.52(L1)	.12(R2)	.21(L1,L2)
	50	.53(L1)	.10(R2,L4)	.24(L2)
	55	.54(L1)	.12(L4)	.28(L1)
	60	.55(L1)	.16(L4)	.30(L1)
	65	.57(L1)	.19(L4)	.33(L2)
U-30C	40	.55(L1)	.16(R2)	.22(L2)
	45	.55(L1)	.14(R2)	.24(L2)
	50	.55(L1)	.12(R2,R5)	.27(L2)
	55	.54(L1)	.11(L4)	.28(L2)
	60	.55(L1)	.21(L4)	.32(L2)
	65	.55(L1,L4)	.35(L6)	.43(L2)
E-8	40	.54(L1)	.19(R5)	.22(L1)
	45	.54(L1)	.15(R2)	.24(L1)
	50	.54(L1)	.13(R2)	.26(L1)
	55	.55(L1)	.12(L1,L4)	.28(L1)
	60	.57(L1)	.15(L4)	.30(L1)
	65	.60	.17(L1,L4)	.32(L1)

Note: Designations in brackets denote position at which peak values occur on a right-hand curve.

L, R = Left & Right sides.

1 to 6 = wheel or wheelset, numbered from the lead axle.

1,2 = lead & trail, for truckside only.

TABLE 2.4 - COMPARATIVE ANALYSIS RESULTS (CONTINUED)

(b) 39 ft Wavelength Geometry Defect

LOCOMOTIVE	SPEED (mph)	PEAK VALUES OF SAFETY INDICATORS		
		Wheel L/V	Wheelset L/V	Truck Side L/V
SDP-40F	40	.74(L4)	.20(L1,R5)	.27(L1)
	45	.76(L4)	.22(L1)	.35(L2)
	50	.78(L4)	.24(L4)	.39(L2)
	55	.80(L4)	.30(L4)	.40(L2)
	60	.83(L4)	.34(L4)	.40(L2)
	65	.88(L4)	.39(L4)	.44(L2)
U-30	40	.75(L4)	.22(R2)	.23(L1)
	45	.78(L4)	.21(R2)	.25(L1,L2)
	50	.82(L4)	.23(L4)	.33(L2)
	55	.86(L4)	.29(L4)	.35(L2)
	60	.87(L4)	.34(L4)	.33(L2)
	65	.87(L4)	.39(L4)	.37(L2)
E-8	40	.76(L1,R2)	.22(L1	.27(L1)
	45	.83(L1)	.29(L1)	.36(L1)
	50	.84(L1)	.32(L1)	.42(L1)
	55	.83(L1)	.31(L1,L4)	.39(L1,L2)
	60	.87(L1)	.36(L1,L4)	.39(L2)
	65	.91(L1)	.42(L1,L4)	.41(L1,L2)

Note: Designations in brackets denote position at which peak values occur on a right-hand curve.

L, R = Left & Right sides.

1 to 6 = wheel or wheelset, numbered from the lead axle.

1,2 = lead & trail, for truckside only.

TABLE 2.5 - SENSITIVITY ANALYSIS ON THREE SELECTED PARAMETERS OF THE U-30C LOCOMOTIVE

DESCRIPTION (U-30C Locomotive, 78 ft wavelength defect at 65 mph)	MEASURES OF SAFETY (peak values)		
	Wheel L/V	Wheelset L/V	Truck Side L/V
NOMINAL CASE	.55	.35	.43
MODIFIED LATERAL DAMPING (1) only	.58	.27	.35
MODIFIED VERTICAL STIFFNESS (2)only	.54	.34	.42
MODIFIED PEDESTAL FRICTION (3) only	.55	.36	.42

(1) Addition of hydraulic dampers in the lateral secondary suspension, having 3600 lb limiting force.

(2) Primary suspension vertical stiffness reduced from 7920 to 5630 lb/in per journal.

(3) Coulomb friction coefficient increased from 0.16 to 0.35.

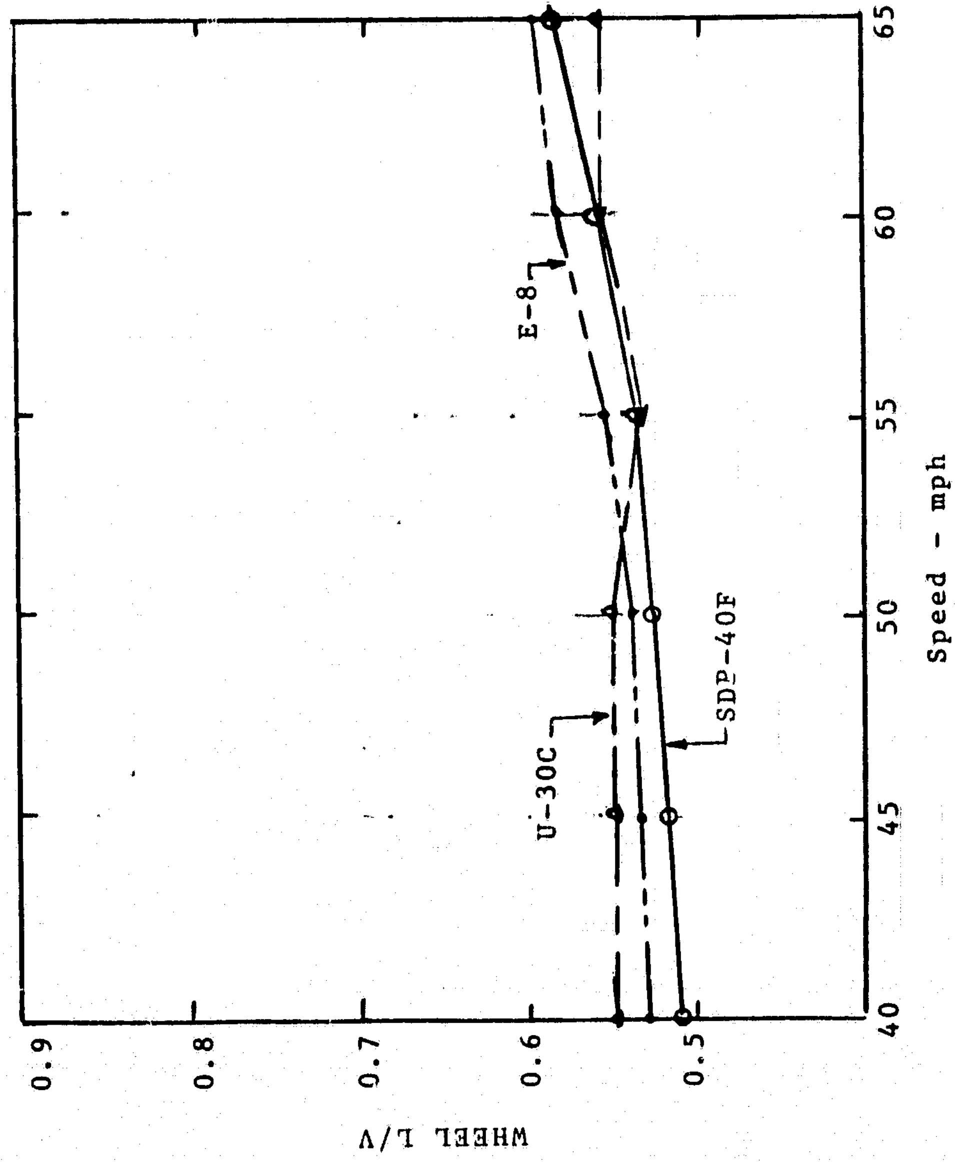

FIGURE 2.1 - PEAK WHEEL L/V RATIO - 78 FT WAVELENGTH COMBINED DEFECTS

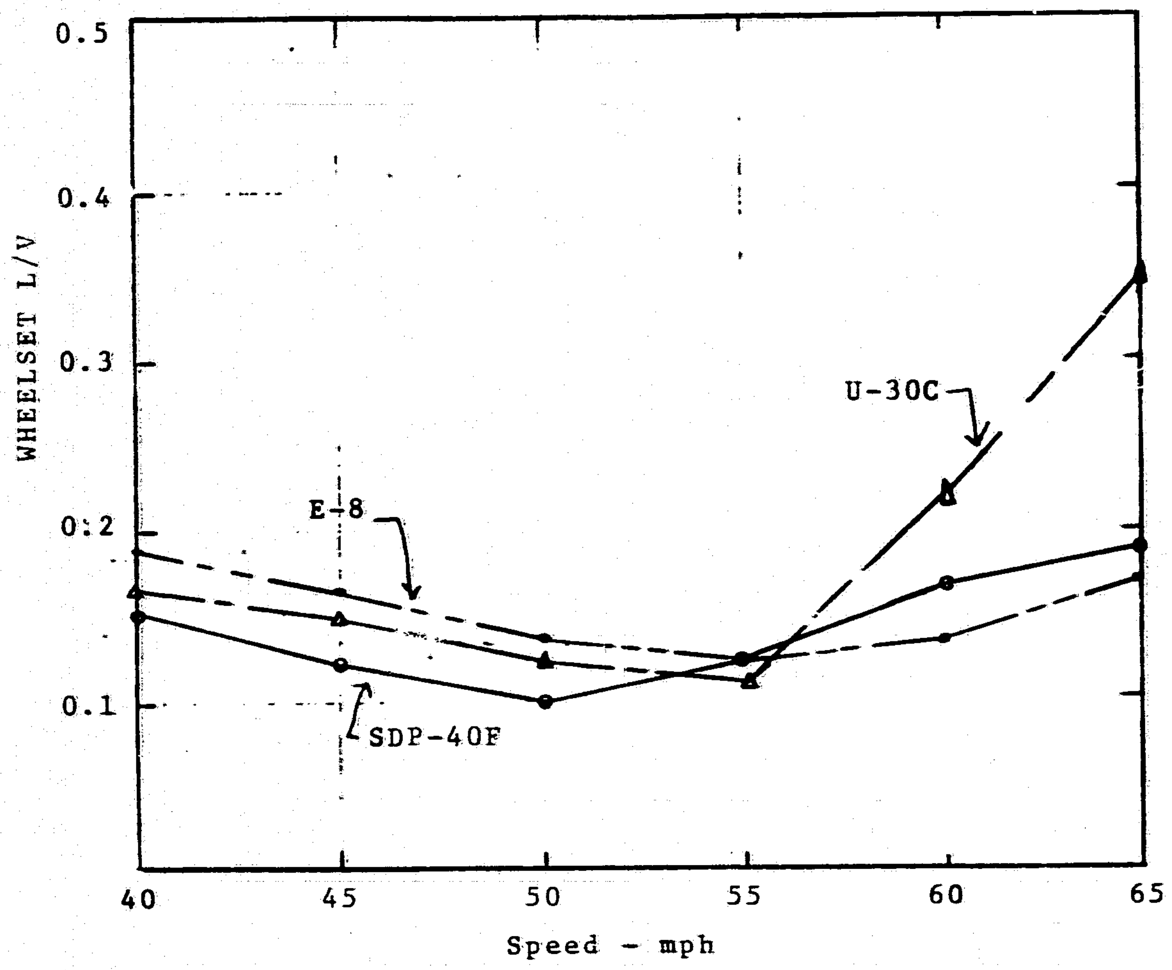

FIGURE 2.2 - PEAK WHEELSET L/V RATIO - 78 FT WAVELENGTH COMBINED DEFECTS

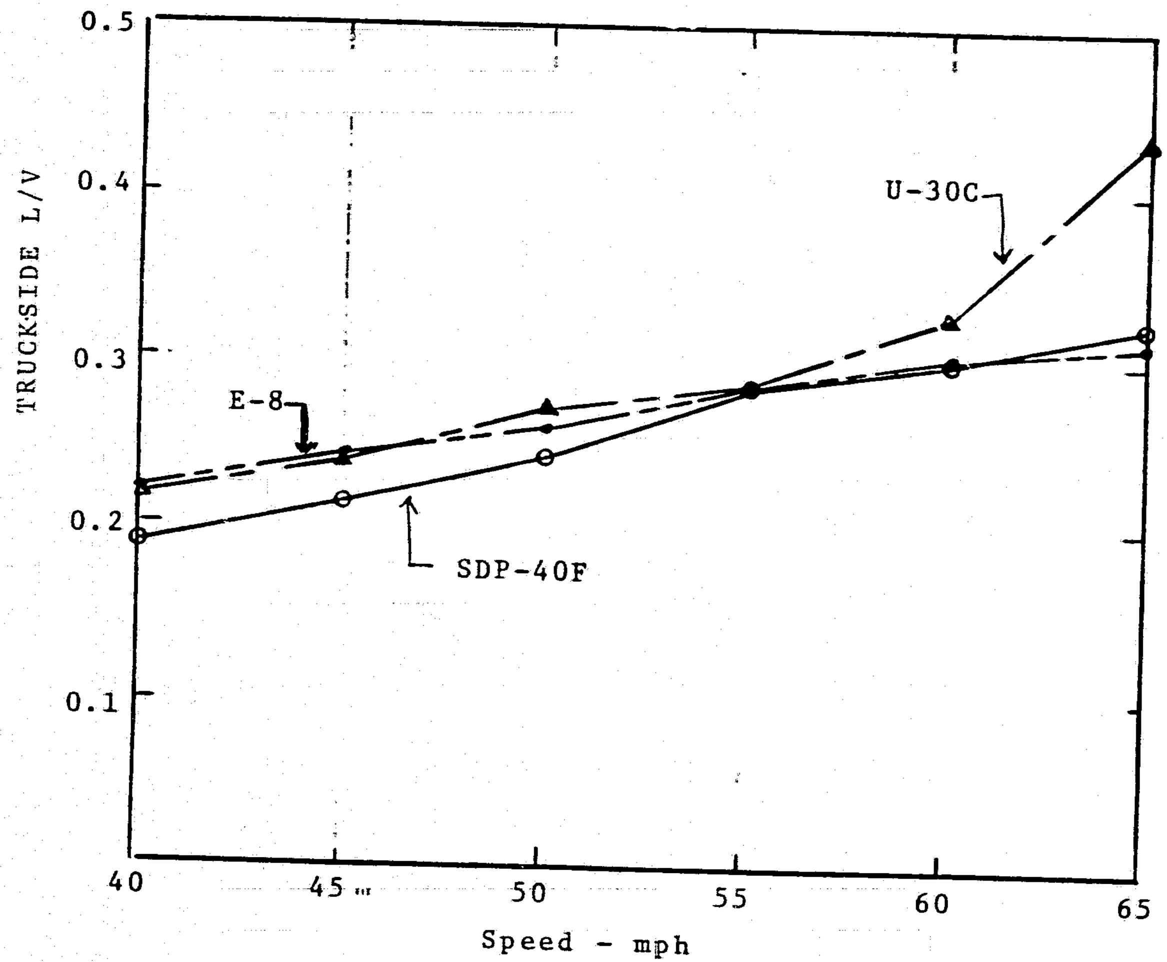

FIGURE 2.3 - PEAK TRUCKSIDE L/V RATIO - 78 FT WAVELENGTH COMBINED DEFECTS

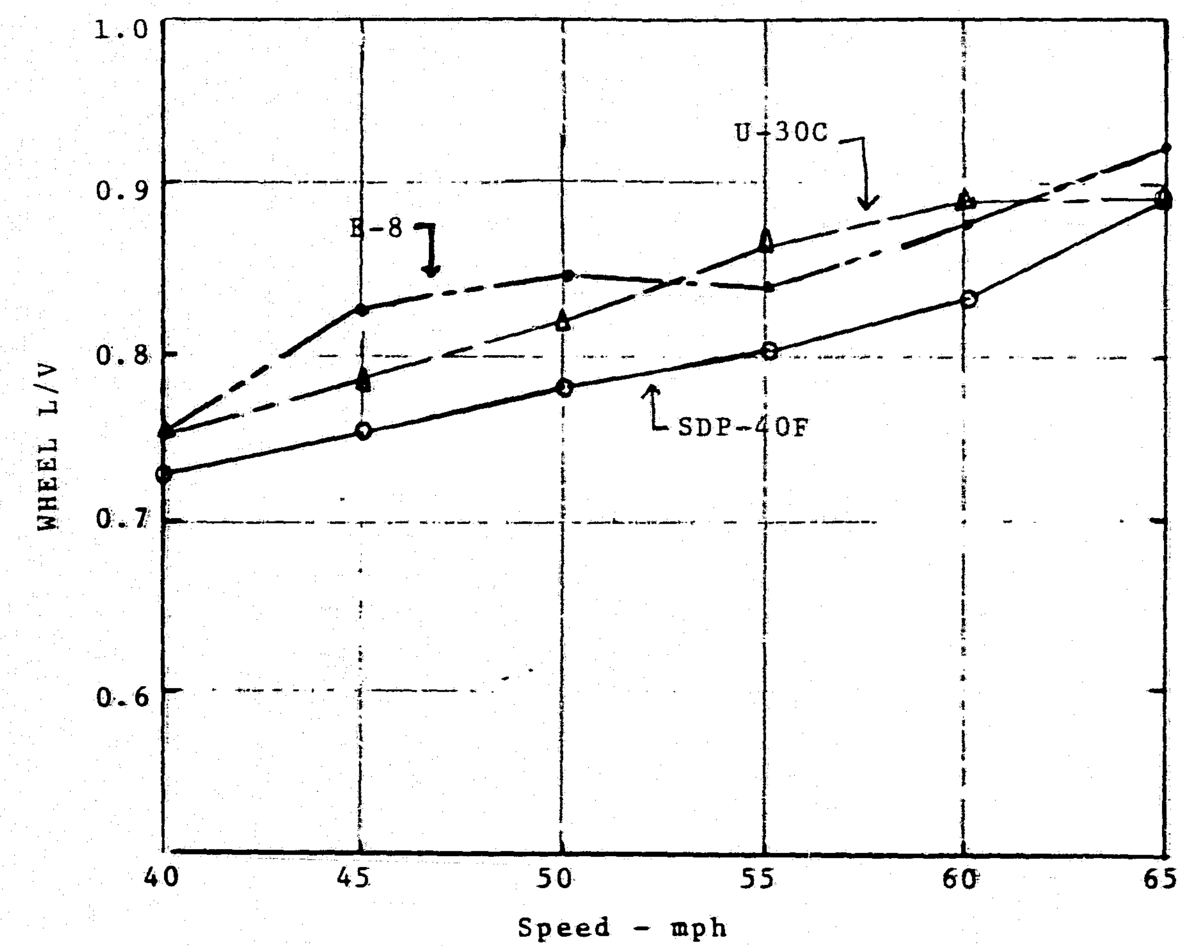

FIGURE 2.4 - PEAK WHEEL L/V RATIO - 39 FT WAVELENGTH COMBINED DEFECTS

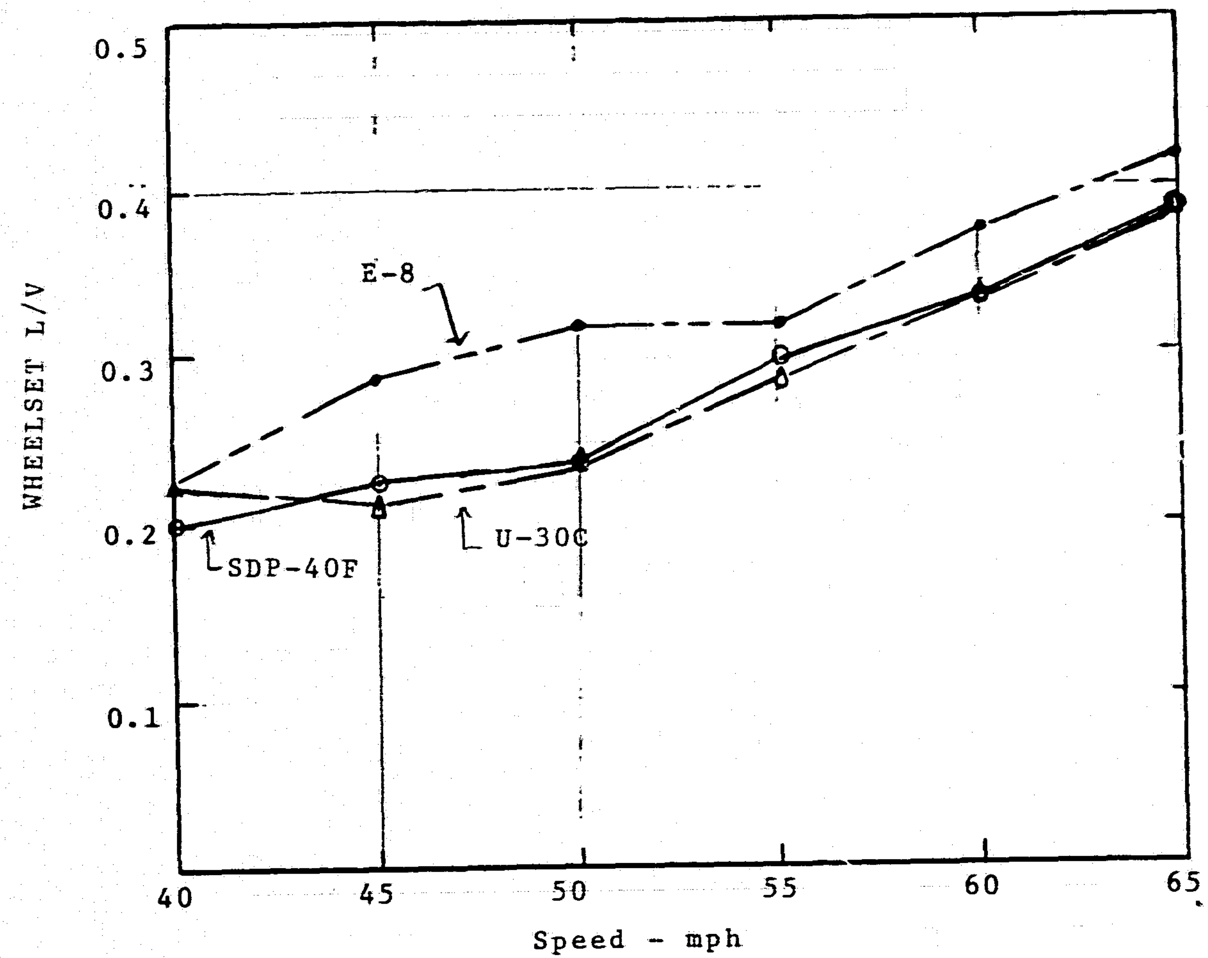

FIGURE 2.5 - PEAK WHEELSET L/V RATIO - 39 FT WAVELENGTH COMBINED DEFECTS

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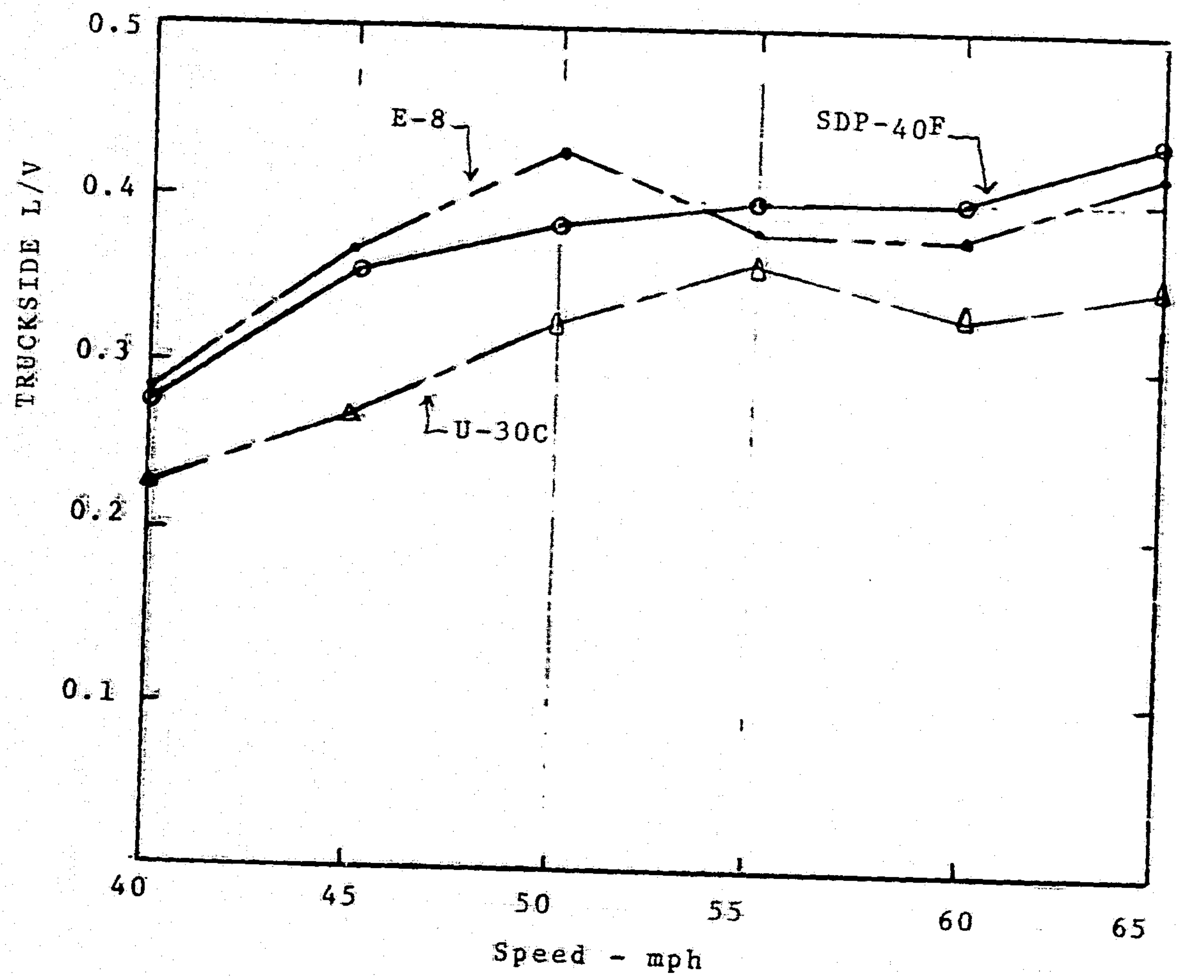

FIGURE 2.6 - PEAK TRUCKSIDE L/V RATIO - 39 FT WAVELENGTH COMBINED DEFECTS

Appendix 3 - General Software Description

	Pg
3.1 Overall Program Operation and Structure	3-2
3.2 Derivatives of State Variables	3-12
3.3 Input Procedures and Output Formats	3-21
3.4 Computer Resource Requirements	3-40

APPENDIX 3

GENERAL SOFTWARE DESCRIPTION

This section describes the software used to implement the locomotive model. Presently, there are two programs, the first of which accepts the parameters defining a particular run with a particular locomotive, and performs the integration which constitutes the run. This program outputs most of its results to a disc file, which is used by the second program to plot selected variables versus time. This chapter deals only with the first or main program as it contains the model itself.

The specification of input parameters is effected through two mechanisms. In the case of parameters defining the three locomotives under study, default sets of parameters are specified within the program itself. All other input, including the specification of which set to use and the definition of track defects and of operational parameters (e.g. locomotive speed, nominal track curvature, etc.) is made by the operator via the terminal.

Output from the program has three destinations. Some output goes to the terminal, especially as required for interaction. A second group of data, including lists of all parameters specifying the particular run and the summary output of peak L/V ratios, is output to a disc file for subsequent (optional) listing, either to the terminal or to a high-speed printer. This file (file #6) may be

saved for future reference. Most of the output from the program, however, is written to a second disc file (file #8) for further processing off-line. This information consists of blocks of data defining the state of the locomotive at fixed intervals during the run. Presently, these data are used off-line to generate the plots of selected variables versus time.

A heading identifying the run number and date and time of execution is written to the terminal and to both disc files. This heading ensures positive identification of data after a run.

Except for a flowchart of the main features of the program, the descriptions of the software in sections 3.1 and 3.2 are expressed in terms of the program structure. Anyone with a rudimentary appreciation of computer programs should have no trouble following the description of the structure and of the individual software modules.

3.1 OVERALL PROGRAM OPERATION AND STRUCTURE

A flowchart showing the major operations of the program is given in Figure 3.0.

At the beginning of a run the operator defines parameters relating to the vehicle, track, and integration which specify the run. Subsequently, other required parameters are calculated and the operator specifies the initial conditions for the locomotive. At this point, all the input parameters are reported and integration can begin.

Each step of the integration entails the calculation of the items in the fourth box in Figure 3.0, the peak L/V

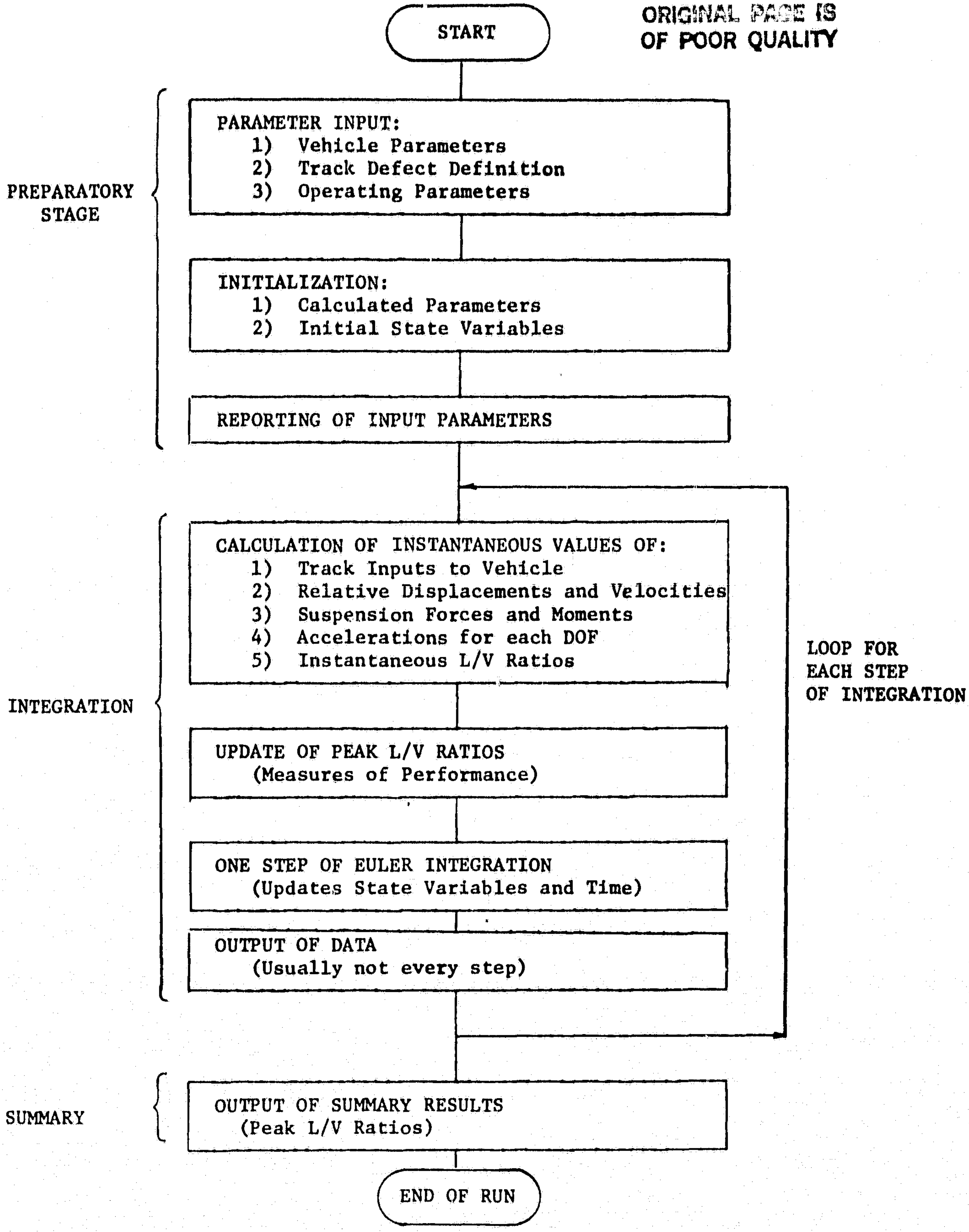

FIGURE 3.0 - COMPUTER CODE FLOW CHART

ratios (the measures of performance) are updated, and one step of Euler integration is performed. Output of the variables describing the state of the locomotive is also performed, although usually less frequently than each integration step (this frequency is one of the operator-specified parameters). The above process is repeated until the run is complete, at which time a summary of the peak L/V ratios is output.

These operations are described in more detail below.

The balance of this section describes the structure of the major elements of the program which simulates the dynamic response of a locomotive. We can group the major tasks into five categories as follows:

1. Specification of Input Parameters.

2. Initialization prior to Integration.

3. Reporting of Input Parameters.

4. Integration and Output during the Integration Process.

5. Summary reporting at the end of a run.

These five basic categories are dealt with in detail in subsections 3.1.1 through 3.1.5 below.

Figure 3.1 shows the structure (or hierarchy) of the major elements of the program. This figure indicates that the main program (SMAIN) has control over twelve major elements which are grouped into the five categories mentioned above and labelled at the top of each column. In two cases, a second level in the hierarchy is shown; specifically, the routine SINVP has control over SPLIST and the integration algorithm (SEULER) has control over the routine responsible for providing the instantaneous derivatives of the state variables (SCALCD).

Detailed descriptions of the functions of the individual routines in the five basic categories are contained under 3.1.1 through 3.1.5.

3.1.1 Specification of Input Parameters

The first function of the main program is to allow the operator to specify the parameters required for a specific run. These parameters fall into three categories the input of which are handled by the following three routines:

1) SINVP allows the operator to specify those parameters which describe the dimensional, inertial, and suspension characteristics of the locomotive to be modelled.

   This routine allows the operator to choose one of three sets of default parameters (over 100 parameters are involved), and also allows him to specify individual parameters at his discretion.

   SINVP uses the routine SPLIST to list the parameters on the terminal if this is requested by the operator.

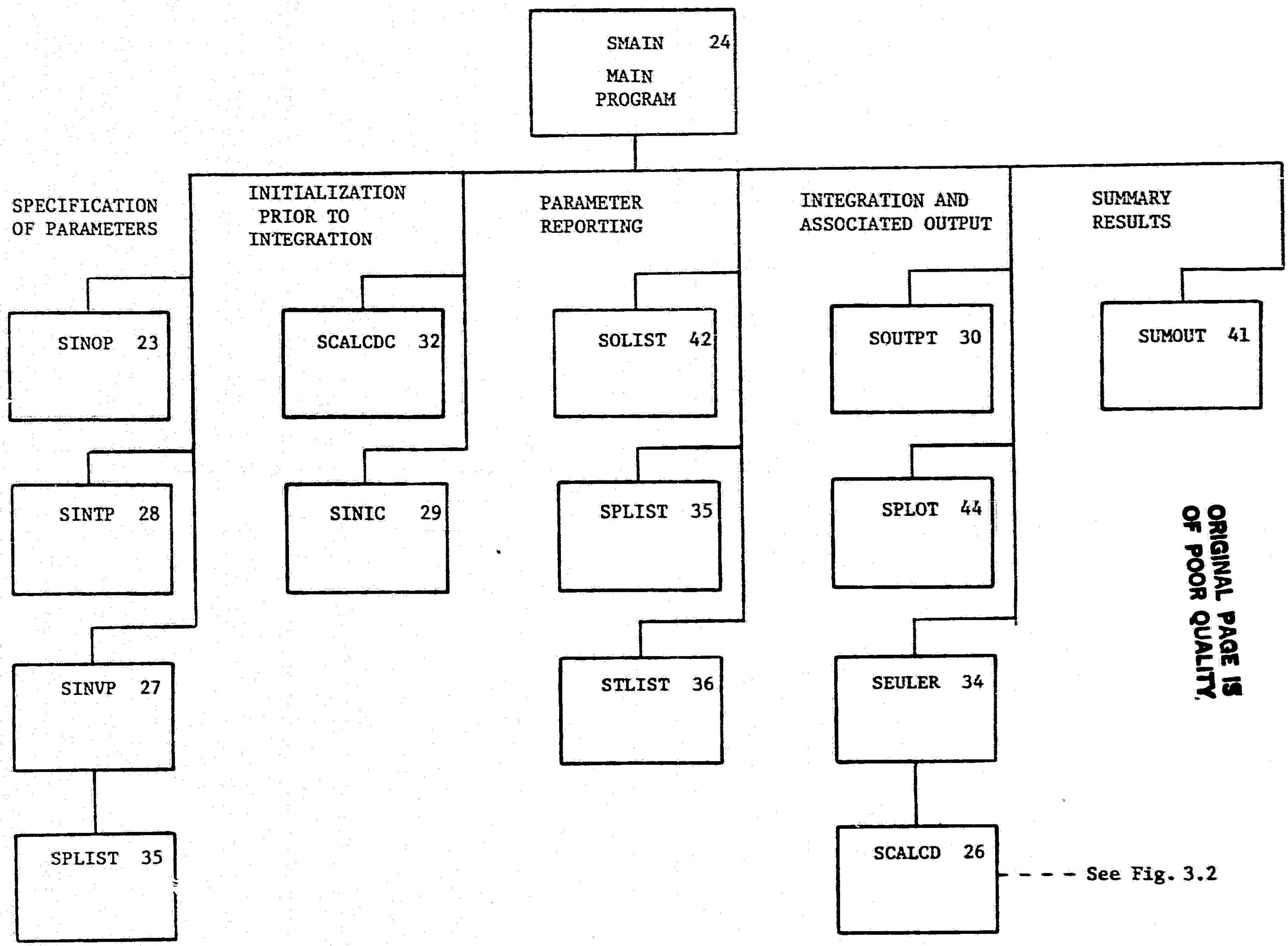

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FIGURE 3.1 - STRUCTURE

2) SINTP allows the operator to specify the track defect definitions. Presently, the program allows up to a total of 25 separate defects to be specified for any single run. Each defect is defined by its type (e.g. vertical, cross-level,etc.), its class (e.g. versed sine, ramp, step, etc.), the position of the beginning of the defect (or defects) on track, and the wavelength, amplitude, and number of defects to be repeated.

3) The third input routine, SINOP, allows the specification of operational parameters including:

- Locomotive speed
- Nominal track curvature
- Nominal track superelevation
- Total time for integration
- Time interval for integration
- Time interval for output during integration
- Locomotive tractive effort.

The main program's only function, for this category, is to call the above three routines.

3.1.2 Initialization Prior to Integration

This group (the second column in Figure 3.1) provides for the initialization of parameters and allows the specification of the initial state variables.

1) The routine SCALCDC calculates a number of secondary parameters which are derived from the parameters described in section 3.1.1. For example, the locomotive velocity (specified in units of miles per hour)

is converted to units of feet per second and this converted value is stored for later computation. This routine is used to avoid the recalculation of such secondary parameters at each iteration.

2) The other routine in this category is SINIC, which is responsible for the balance of the initialization required prior to integration. The variables initialized fall into the following categories:

a) State Variables

The thirty state variables are all initialized to zero and the operator is given the opportunity to modify as many as he wishes.

b) Variables required for the first Step of Integration

Some of the variables used in the calculations are not calculated prior to their use within one integration step, and normally the values from the previous step are used. These variables must be initialized prior to the first step of integration. Specifically, these are:

- the vertical wheel loads
- the longitudinal creep forces at the wheel treads
- the primary forces at each axle box in the lateral and longitudinal directions
- a variable describing the rotational velocity of each of the locomotive axles.

C-2

c) Time Variables

The time for integration is initialized to zero and the print time is also initialized.

d) Special Error Flags

Five flags are provided in the software to indicate error conditions, and all are initialized to zero. At this time, only two of these are in use, and they flag instances of wheel unloading and primary vertical unloading.

e) Variables used to provide the Measures of Evaluation

There are numerous variables which are used internally to the program in order to calculate the filtered L/V ratios used for evaluation of safety. These are initialized here.

The function of the main program for this category is to call the SCALCD and SINIC and to request the run number from the operator.

3.1.3 Reporting of Input Parameters

Prior to the beginning of the integration, the main program reports the input parameters as part of the standard output. The current data and time are requested from the operating system, and a heading also containing run number and locomotive type code is output. This is followed by the calling of the following three routines which list their output to a file for later use.

1) The routine SPLIST is used to output all of the locomotive parameters set up through the use of SINVP. (Note that SPLIST appears twice in Figure (1); it is used both by SINVP as described under 3.1.1, and also by the main program).

2) The routine STLIST is used to keep a record of all the track defects specified through the use of SINTP.

3) SOLIST outputs the operational parameters: locomotive speed, curvature, nominal superelevation, length of track, integration time step and printing time step, and tractive effort.

The calling of these three routines concludes the reporting of input parameters.

3.1.4 Integration and Associated Output

Having completed the functions described above, all parameters are initialized and integration may begin. The main program is responsible for calling the routines in the fourth column of Figure 3.1 to perform each integration step (SEULER) and to provide the output of variables during integration (SOUTPT and SPLOT).

SMAIN initially calculates the number of integration steps required, and then a loop is executed for each step. Within the loop, a check is made to see if the incremental time for printing has elapsed; if so, any requisite output is performed through SPLOT and/or SOUTPT (as of September 17, 1980, SOUTPT is not in use). Also within the loop a call is made to the integrator (SEULER), which performs one

step of integration and updates all the state variables and the time. SEULER uses SCALCD to provide the instantaneous derivatives of the state variables at every step.

- Output routines:

1) SOUTPT

This routine is used to list various state variables and forces to a specified output device. This routine was originally used to print results to the terminal during integration as an aid in debugging; it is not presently in use and only SPLOT is used for output during integration.

2) SPLOT

This routine collects 260 variables which describe the state of the locomotive and outputs these to a disc file for later off-line processing. This processing presently consists of plotting selected variables versus time. The data saved on disc by SPLOT includes most of the variable data in the program.

- Integrator

3) SEULER

This routine calls the routine responsible for the provision of current values of the state variables (SCALCD), performs one Euler integration step on the thirty state variables, and increments the

integration time before returning control to the main program. It is called at every integration step.

The routine SCALCD is treated separately under section 3.2 below.

3.1.5 Summary Reporting at the End of a Run

At the end of a run, when integration has proceeded for the specified time, some of the data is listed to the file used for printing which includes the error flags and the peak values and times of the evaluation measures (the L/V ratios). This having been effected by SUMOUT, the run is concluded.

3.2 DERIVATIVES OF STATE VARIABLES

The routine SCALCD is responsible for the calculation of the derivatives of all the state variables. This routine makes use of several other routines as shown in Figure 3.2, which fall into five major categories as follows:

1. Definition of instantaneous track defect inputs to the individual axles.

2. Calculation of the relative displacements (or rotations) and velocities at interconnections.

3. Calculation of the relative forces (or moments) at the interconnections.

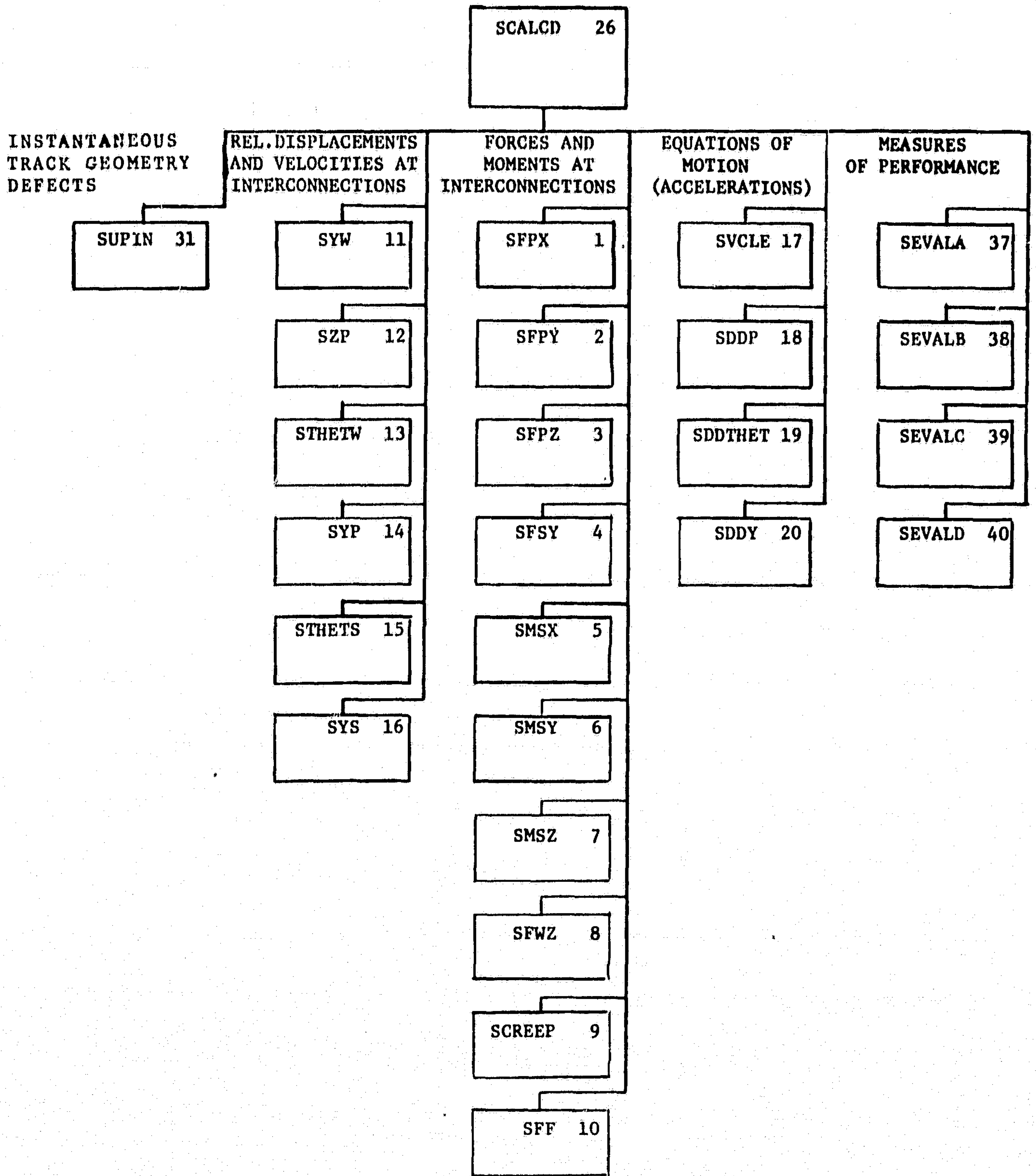

FIGURE 3.2 - STRUCTURE

4. Calculation of the absolute accelerations for each degree of freedom.

5. Calculation of measures of performance .

These five categories are covered in subsections 3.2.1 through 3.2.5 below, and correspond to the five columns in Figure 3.2.

3.2.1 Instantaneous Track Defects

Given the instantaneous position of the locomotive on track, SUPIN determines the displacement, velocity, and acceleration terms corresponding to all track defects under each of the six axles. There is provision for defects in cross-level, vertical alignment, lateral alignment, and gage.

3.2.2 Relative Displacements and Velocities

The routines in the table below are used to calculate the instantaneous relative displacements (or rotations) and velocities at the various interconnections in the model, given the state variables (absolute displacements and velocities), and the instantaneous track defects.

ROUTINE NAME	INTERCONNECTION	DIRECTION
SYW	WHEEL/RAIL	LATERAL
SZP	PRIMARY	VERTICAL
STHETW	WHEEL/RAIL	YAW
SYP	PRIMARY	LATERAL
STHETS	SECONDARY	YAW
SYS	SECONDARY	LATERAL

The relative displacements and velocities are calculated once per step and are used to determine the interconnection forces and moments.

3.2.3 Forces and Moments at Interconnections

The ten routines in this group calculate the forces and moments at the suspension interconnections. Some of these forces and moments are calculated from relative displacements (or rotations) and relative velocities at the interconnections and the constitutive relationships describing the suspension characteristics (for instance, vertical primary loads are calculated based on spring deflections and friction). Others are calculated on the basis of force and moment equilibrium (for instance, secondary pitch moments are calculated based on the difference between the primary vertical loads for the end axles of each truck).

The following table indicates which routines calculate which forces and moments.

ROUTINE NAME	INTERCONNECTION	FORCE/MOMENT
1) SFPX	PRIMARY	LONGITUDINAL FORCES
2) SFPY	PRIMARY	LATERAL FORCES
3) SFPZ	PRIMARY AND SECONDARY	VERTICAL FORCES VERTICAL FORCES
4) SFSY	SECONDARY	LATERAL FORCES
5) SMSX	SECONDARY	ROLL MOMENTS
6) SMSY	SECONDARY	PITCH MOMENTS
7) SMSZ	SECONDARY	YAW MOMENTS
8) SFWZ	WHEEL/RAIL	VERTICAL WHEEL LOADS
9) SCREEP	WHEEL/RAIL	LONGITUDINAL TREAD CREEP FORCES AND LATERAL TREAD CREEP FORCES
10) SFF	WHEEL/RAIL	LATERAL FLANGE FORCES

1) SFPX

This routine calculates the longitudinal pedestal forces which, because of pedestal friction, provide damping in the lateral and vertical primary suspension. Because there is no primary longitudinal suspension in the model, these forces are calculated based on the following equilibrium conditions:

a) The sum of the two primary longitudinal forces on any axle equals the nominal tractive effort for that axle, and

b) The difference between the primary longitudinal forces on an axle is due to a moment resulting from the inertial forces and wheel/rail forces acting on the wheelset.

2) SFPY

This routine calculates the lateral primary forces at each axle box due to free play, stiffness and damping between the axle and axle box, and pedestal friction.

3) SFPZ

This routine calculates the primary vertical forces at each axle box based on the nonlinear vertical stiffness characteristic including stops, friction, and optional external dampers. The secondary vertical force acting on the vehicle from each truck is also calculated here.

4) SFSY

SFSY calculates the lateral secondary forces including a nonlinear stiffness term with stops and damping terms due to the rubber suspension, friction, and any external damper.

5) SMSX

This routine calculates the roll moment transmitted to the car body by the truck frame due to primary loads in the vertical and lateral directions.

6) SMSY

This routine calculates the pitch moment transmitted to the car body by the truck frame due to primary vertical loads.

7) SMSZ

This routine calculates the yaw moment at the center plate due to friction.

8) SFWZ

This routine calculates the vertical wheel loads at each wheel from the primary vertical loads, the acceleration of the wheelset vertically (including gravity), the roll inertia and acceleration of the wheelset and the lateral tread and flange forces. The model assumes no wheel-lift, and an error is flagged if wheel-lift occurs.

9) SCREEP

SCREEP calculates the longitudinal and lateral forces between the wheel tread and the rail at each wheel based on the following: vertical wheel loads, the relative lateral displacement of the wheel and the rail, the lateral velocity of the wheelset, and a variable describing the slip velocity of each wheelset. This slip parameter is also updated by SCREEP.

10) SFF

This routine calculates the lateral flange force at each wheel.

3.2.4 Accelerations for each Degree of Freedom

These four routines contain the equations of motion of the system which are of the form

$$a = F/m$$

or

$$\alpha = M/I$$

where a = acceleration, F = force, m = mass, or
α = angular acceleration, M = moment,
I = moment of inertia.

The routines are as follows:

1) SVCLE

This routine calculates the accelerations for the five locomotive body degrees of freedom.

2) SDDP

This routine calculates the lateral accelerations of the truck frames.

3) SDDTHET

This routine calculates the yaw accelerations of the truck frame and wheelset assemblies.

4) SDDY

This routine calculates the lateral accelerations of the six wheelsets.

The calculation of these accelerations allows SCALCD to provide all the state variable derivatives. For displacements, the derivatives are simply the corresponding velocity state variables; for velocities, the derivatives are the accelerations calculated above.

3.2.5 Calculation of Measures of Performance

The four routines which make up this group are used to generate the L/V ratios which are used as measures of performance. The routines define instantaneous lateral and vertical forces, generate the various instantaneous L/V ratios, filter this data, and preserve the values and times of peak values. This information is presented in the summary output (section 3.1.5).

3.3 INPUT PROCEDURES AND OUTPUT FORMATS

This section is divided into two parts. The first of these describes the options available to the operator for definition and modification of input data. The second includes sample output displays and describes their formats.

3.3.1 Input Procedures

As described briefly in section 3.1, there are four different types of interactive input between the operator and the program.

These four shall be dealt with in this section, in the order in which they occur during program operation:

1. Vehicle Parameters
2. Track Defect Definition
3. Operational Parameters
4. State Variable Initial Conditions

1) Vehicle Parameters

Vehicle parameters are defined by the operator from the routine SINVP. He is initially requested to enter the number of a default set of parameters; presently there are three sets corresponding to an SDP-40F with the new HTC trucks, the U-30C locomotive, and the E-8 locomotive in that order.

Having selected a default set, the operator has the option to list the parameters, change an individual parameter or parameters, or exit SINVP. If he opts to list the parameters, he is subsequently again given the option to list, change, or exit. If he opts to change parameters, he identifies the parameter of group of parameters by number (see section 3.3.2.1) and specifies the desired parameter value.

This approach to vehicle parameters relieves the operator from having to specify each of 111 parameters while retaining complete flexibility.

2) Track Defect Definition

Any combination of track defects may be introduced into the piece of track to be traversed by the locomotive through the specification of six data for each:

a) Type

The defect type indicates whether a specified defect is a defect in crosslevel (type 1), lateral alignment (type 2), vertical alignment (type 3), or gage (type 4).

b) Class*

The class of the defect indicates its shape. Presently the classes available are: versine (class 1), ramp (class 2), sinusoid (class 3), and step (class 4).

c) Starting Position

The beginning of the defect is specified in terms of feet along the track profile from the initial position of the lead axle.

d) Amplitude

This value is the total amplitude of the defect in inches. The sign convention is as follows:

	Type of defect	Positive amplitude
1.	Crosslevel	left rail elevated
2.	Lateral alignment	track deflected to the left
3.	Vertical alignment	track deflected upwards
4.	Gage	wide gage

*Note that this is not the FRA track safety standard classification.

For crosslevel defects, the crosslevel angle of the track is calculated assuming a nominal track gauge of 59½".

e) Wavelength
This value is the total length, in feet, of a single defect. It is not meaningful for step defects.

f) Number of defects
The defect specified may be repeated, and this value indicates the number of consecutive identical defects.

For example, the specification:

Type	- 2
Class	- 1
Start	- 100
Amplitude	- 0.5
Wavelength	- 39
Number	- 4,

defines a group of four consecutive 39-foot versine defects in lateral track alignment where each defect has an amplitude of ½ inch and the first defect starts 100' from the starting location of the lead axle.

Presently, the operator may specify from zero to 25 such defects interactively for each run, and defects may be superimposed even if they are of the same type.

3) Operational Parameters

The following parameters are specified interactively by the operator:

- Locomotive speed - m.p.h.
- Track curvature - degrees per 100 ft chord
- Track superelevation - inches in 59½"
- Tractive effort - lb
- Lateral wind load - lb
- Lateral component of lead coupler force - lb
- Lateral component of trail coupler force - lb
- Total simulation time - seconds
- Integration step size - seconds
- Time interval for printing - seconds

The last three are seconds of simulated time, not seconds of computer time.

4) State Variable Initial Conditions

Table 3.1 lists the thirty state variables corresponding to the fifteen degrees of freedom. As a rule, these are initialized to zero at the beginning of any run, but the operator may interactively redefine any of them.

#	SYMBOL	DESCRIPTION	POSITIVE DIRECTION	UNITS
1	y_1	1st Wheelset lateral displacement	left	in.
2	y_2	2nd Wheelset lateral displacement	left	in.
3	y_3	3rd Wheelset lateral displacement	left	in.
4	y_4	4th Wheelset lateral displacement	left	in.
5	y_5	5th Wheelset lateral displacement	left	in.
6	y_6	6th Wheelset lateral displacement	left	in.
7	p_1	Lead truck lateral displacement	left	in.
8	p_2	Trail truck lateral displacement	left	in.
9	θ_1	Lead truck yaw rotation	left	radians
10	θ_2	Trail truck yaw rotation	left	radians
11	Y	Locomotive body lateral displacement	left	in.
12	Z	Locomotive body vertical displacement	up	in.
13	α	Locomotive body roll rotation	right	radians
14	β	Locomotive body pitch rotation	forward	radians
15	γ	Locomotive body yaw rotation	left	radians
16	$\dot{y}_1$	1st Wheelset lateral velocity	left	in/sec.
17	$\dot{y}_2$	2nd Wheelset lateral velocity	left	in/sec.
18	$\dot{y}_3$	3rd Wheelset lateral velocity	left	in/sec.
19	$\dot{y}_4$	4th Wheelset lateral velocity	left	in/sec.
20	$\dot{y}_5$	5th Wheelset lateral velocity	left	in/sec.
21	$\dot{y}_6$	6th Wheelset lateral velocity	left	in/sec.
22	$\dot{p}_1$	Lead truck lateral velocity	left	in/sec.
23	$\dot{p}_2$	Trail truck lateral velocity	left	in/sec.
24	$\dot{\theta}_1$	Lead truck yaw velocity	left	radians/sec.
25	$\dot{\theta}_2$	Trail truck yaw velocity	left	radians/sec.
26	$\dot{Y}$	Locomotive body lateral velocity	left	in/sec.
27	$\dot{Z}$	Locomotive body vertical velocity	up	in/sec.
28	$\dot{\alpha}$	Locomotive body roll velocity	right	radians/sec.
29	$\dot{\beta}$	Locomotive body pitch velocity	forward	radians/sec.
30	$\dot{\gamma}$	Locomotive body yaw velocity	left	radians/sec.

TABLE 3.1 - STATE VARIABLES

3.3.2 Output Formats

As described briefly in section 3.1, there are five types of output from the program to the terminal and to the disc files.

These five are presented in exhibits with accompanying discussion in the following subsections:

1. Vehicle Parameter Output
2. Track Defects Output
3. Operational Parameter Output
4. Summary of Results
5. Output during Integration

1) Vehicle Parameter Output

Exhibit 3.3.2.1 shows the format of the heading output by the main program for run identification in the first three lines of the exhibit, and the balance of the exhibit shows the output of the vehicle parameters.

This is identical to the interactive output available at the terminal during specification of the vehicle parameters, and the indices on the right are used for parameter modification. The list is divided into geometric parameters, inertial parameters, and suspension parameters.

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PROGRAM DSL-2 (REVISION DATE: AS OF SEPT.29TH, 1980)
RUN # : 262 OF 80/09/30. 13.18.07.

LOCOMOTIVE PARAMETERS SET NUMBER: 1

LOCOMOTIVE PARAMETERS SET NUMBER: 1

DESCRIPTION		UNITS	VALUE	INDEX
GEOMETRIC PROPERTIES				
LOCOMOTIVE BODY				
COUPLER PIN/CG-LONG.		IN	404.000	1
SECONDARY/CG-VERT.		IN	50.200	2
PRIMARY/SECONDARY-VERT.		IN	7.500	3
COUPLER/RAIL-VERT.		IN	34.500	4
CENTER OF PRESSURE/RAIL-VERT.		IN	120.000	5
TRUCK CENTER/CG-LONG.		IN	276.000	6
TRUCK FRAMES				
HALF TRUCK WHEELBASE		IN	82.200	7
HALF LATERAL SPACING		IN	39.500	8
THICKNESS OF SHIMS	LEFT AXLE 1	IN	0.000	9
IN THE VERTICAL	2	IN	0.000	10
PRIMARY SUSPENSION	3	IN	0.000	11
	4	IN	0.000	12
(POSITIVE WHEN	5	IN	0.000	13
SHIMS ADDED)	6	IN	0.000	14
	RIGHT 1	IN	0.000	15
	2	IN	0.000	16
	3	IN	0.000	17
	4	IN	0.000	18
	5	IN	0.000	19
	6	IN	0.000	20
WHEELSET/TRACTION MOTOR ASSEMBLY				
NOMINAL TREAD RADIUS		IN	20.000	21
WHEEL TREAD CONICITY		IN	.050	22
DIFFERENCE IN MEAN	AXLE 1	IN	0.00	23
ROLLING RADIUS FROM	2	IN	0.00	24
NOMINAL	3	IN	0.00	25
(POSITIVE WHEN LARGER	4	IN	0.00	26
THAN NOMINAL)	5	IN	0.00	27
	6	IN	0.00	28
MISMATCH IN WHEEL ROLLING	AXLE 1	IN	0.000	29
RADIUS FROM SIDE TO SIDE	2	IN	0.000	30
(POSITIVE WHEN WHEEL ON	3	IN	0.000	31
LEFT RAIL IS LARGER THAN	4	IN	0.000	32
THAT ON RIGHT RAIL)	5	IN	0.000	33
	6	IN	0.000	34
TRACK				
HALF KINEMATIC GAUGE		IN	29.75	35
RAILHEAD CROWN RADIUS		IN	10.00	36

EXHIBIT 3.3.2.1 - VEHICLE PARAMETER OUTPUT

(page 1 of 3)

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MASS PROPERTIES

LOCOMOTIVE BODY				
WEIGHT		LB	295700.	37
ROLL MOMENT OF INERTIA		LB-IN-SEC2	1510000.	38
PITCH MOMENT OF INERTIA		LB-IN-SEC2	35300000.	39
YAW MOMENT OF INERTIA		LB-IN-SEC2	35300000.	40
TRUCK FRAMES				
WEIGHT		LB	15440.	41
ROLL MOMENT OF INERTIA		LB-IN-SEC2	52655.	42
PITCH MOMENT OF INERTIA		LB-IN-SEC2	161400.	43
YAW MOMENT OF INERTIA		LB-IN-SEC2	161400.	44
WHEELSET/TRACTION MOTOR ASSEMBLY				
WEIGHT	AXLE 1	LB	13124.	45
	2	LB	13124.	46
	3	LB	13124.	47
	4	LB	13124.	48
	5	LB	13124.	49
	6	LB	13124.	50
ROLL MOMENT OF INERTIA	AXLE 1	LB-IN-SEC2	20000.	51
ABOUT CG	2	LB-IN-SEC2	20000.	52
	3	LB-IN-SEC2	20000.	53
	4	LB-IN-SEC2	20000.	54
	5	LB-IN-SEC2	20000.	55
	6	LB-IN-SEC2	20000.	56
OFFSET OF CG FROM	AXLE 1	IN	10.0	57
AXLE CENTERLINE	2	IN	10.0	58
	3	IN	10.0	59
(POSITIVE WHEN MOTOR	4	IN	-10.0	60
TRAILS AXLE)	5	IN	-10.0	61
	6	IN	-10.0	62
YAW MOMENT OF INERTIA	AXLE 1	LB-IN-SEC2	16780.0	63
	2	LB-IN-SEC2	16780.0	64
	3	LB-IN-SEC2	16780.0	65
	4	LB-IN-SEC2	16780.0	66
	5	LB-IN-SEC2	16780.0	67
	6	LB-IN-SEC2	16780.0	68

EXHIBIT 3.3.2.1 (CONTINUED)

(page 2 of 3)

SUSPENSION PROPERTIES

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SECONDARY			
LATERAL			
STIFFNESS			
RUBBER STIFFNESS	LB/IN	15500.	69
SPRING TRAVEL TO STOP(EACH SIDE)	IN	1.250	70
STIFFNESS BEYOND STOP	LB/IN	150000.	71
DAMPING			
VISCOUS COEFFICIENT (RUBBER)	LB/(IN/SEC)	136.	72
FRICTION BOLSTER COEFFICIENT	--	.40	73
LVB COEFFICIENT FOR BOLSTER FRICTION	LB/(IN/SEC)	4000.	74
YAW DAMPING			
ROTATIONAL FRICTION FACTOR	IN-LB/LB	1.10	75
LVB COEFFICENT	IN-SEC	10000000.	76
EXTERNAL DAMPERS			
VISCOUS COEFFICIENT	LB/(IN/SEC)	1020.	77
LIMITING FORCE	LB	3600.	78
PRIMARY			
LATERAL			
STIFFNESS			
ROLLER BEARING FREE PLAY	IN	.31	79
RUBBER ELEMENTS TRAVEL	IN	.25	80
RUBBER PRELOAD	LB	1500.	81
STIFFNESS BEYOND STOP	IN	100000.	82
DAMPING			
FRICTION FOR ROLLER BEARING	--	.10	83
LVB COEFFICIENT FOR FRICTION	LB/(IN/SEC)	4000.	84
VERTICAL			
STIFFNESS			
AVAILABLE TRAVEL(COMPRESSION)	IN	2.25	85
AVAILABLE TRAVEL(EXTENSION)	IN	2.25	86
SPRING STIFFNESS(PER JOURNAL)	LB/IN	5630.	87
STIFFNESS BEYOND STOP(EITHER WAY)	LB/IN	200000.	88
PEDESTAL DAMPING			
FRICTION COEFFICIENT(PEDESTAL FACE)	--	.35	89
FRICTION COEFFICIENT(SIDE LUG)	--	.35	90
LVB COEFFICIENT FOR TOTAL FRICTION	LB/(IN/SEC)	3000.	91
EXTERNAL DAMPERS (OPTIONAL)			
CODE TO INDICATE THE PRESENCE OR ABSENCE OF EXTERNAL DAMPERS (0=NO DAMPER) (1=DAMPER) — LEFT AXLE 1	--	0.	92
2	--	1.	93
3	--	0.	94
4	--	0.	95
5	--	1.	96
6	--	0.	97
RIGHT 1	--	0.	98
2	--	1.	99
3	--	0.	100
4	--	0.	101
5	--	1.	102
6	--	0.	103
VISCOUS COEFFICIENT (COMPRESSION)	LB/(IN/SEC)	510.	104
VISCOUS COEFFICIENT(EXTENSION)	LB/(IN/SEC)	510.	105
LIMITING FORCE(COMPRESSION)	LB	1800.	106
LIMITING FORCE(EXTENSION)	LB	1800.	107
WHEEL/RAIL			
FLANGE			
FLANGEWAY CLEARANCE(EACH SIDE)	IN	.550	108
STIFFNESS AFTER FLANGE CONTACT	LB/IN	80000.	109
TREAD			
CREEP COEFFICIENT ADJUSTMENT FACTOR	--	.70	110
COULOMB FRICTION COEFFICIENT	--	.30	111

EXHIBIT 3.3.2.1 (CONTINUED)

(page 3 of 3)

2) Track Defect Output

Exhibit 3.3.2.2 is a sample output of the track defects specified for a particular run. In this case, three single defects, each 78' long, have been defined. The first is a crosslevel defect which tilts to the left by 1¼" in 59½"; the second is a lateral defect to the left of 1½", and the last is a vertical dip in the track of 1 3/8".

3) Operational Parameter Output

Exhibit 3.3.2.3 is a sample output of the operational parameters.

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TRACK GEOMETRY DEFECTS

NO.	TYPE	CLASS	START (FT)	AMPLITUDE (IN)	WAVELENGH (FT)	COUNT
1	X-LEVEL	VERSINE	100.	-1.250	39.	1
2	LATERAL	VERSINE	100.	1.500	39.	1
3	VERTICAL	VERSINE	100.	-1.375	39.	1

EXHIBIT 3.3.2.2 - TRACK DEFECT OUTPUT

OPERATIONAL PARAMETER SPECIFICATION

PARAMETER NAME	VALUE	UNITS
LOCOMOTIVE SPEED	40.00	MPH
NOMINAL TRACK CURVATURE	3.00	DEG
NOMINAL TRACK SUPERELEVATION	6.00	IN
TRACTIVE EFFORT	9000.	LB
LATERAL WIND LOAD	0.	LB
LATERAL COUPLER FORCE/LEAD	0.	LB
LATERAL COUPLER FORCE/TRAIL	0.	LB
RUN TIME	5.0000	SEC
TIME STEP	.0010	SEC
PRINT INTERVAL	99.0000	SEC

EXHIBIT 3.3.2.3 - OPERATIONAL PARAMETER OUTPUT

FLAGS 0. 0. 0. 0. 0.

EVALUATION OF SAFETY CRITERIA
PEAK VALUE ANALYSIS

AXLE NO	INDIVIDUAL WHEEL L/V RATIOS				WHEELSET L/V RATIOS				TRUCK SIDE L/V RATIOS			
	RATIOS		TIMES		RATIOS		TIMES		RATIOS		TIMES	
	L	R	L	R	L	R	L	R	L	R	L	R
1	.70	.30	2.12	2.23	.14	.13	2.24	1.83	.23	.21	2.35	2.37
2	.36	.29	2.40	2.39	.05	.22	2.50	2.24				
3	.26	.18	2.57	2.58	.07	.07	2.55	2.99				
4	.75	.30	2.81	3.01	.14	.12	2.93	2.63	.22	.21	3.04	3.06
5	.38	.29	3.13	3.07	.05	.20	3.16	2.90				
6	.23	.17	3.28	3.29	.03	.05	3.27	3.63				

EXHIBIT 3.3.2.4 - SAFETY CRITERIA OUTPUT

4) Summary of Results

Exhibit 3.3.2.4 shows a sample summary output which is divided into two parts.

The first line, labelled "Flags", indicates abnormal conditions which may have occurred during integration. The first flag is a count of instances of wheel unloading, and the second is a count of instances of primary vertical unloading; the other three flags are not presently in use. Since the model assumes that the wheelsets follow the track and that net primary suspension forces on each axle box are always downwards, results from any run with non-zero counts are suspect.

The bulk of the summary output reports peak values of the measures of performance, the various L/V ratios. For each of the L/V ratios, a maximum value and time is specified. For example, the peak L/V ratio that occurred on the right wheel of the second axle was .29 and occurred 2.39 seconds into the run. The peak wheelset L/V ratio on the fifth wheelset tending to shift the track to the left was .05 at 3.16 seconds and to the right was .20 at 2.90 seconds.

5) Output During Integration

During integration there are two types of output which occur as described in section 3.1.4; these are generated by the routines SOUTPT and SPLOT.

a) SOUTPT

Exhibit 3.3.2.5.1 is a sample output from SOUTPT which is used for more detailed analysis.

The first line indicates the time of the output and the current state of the five flags discussed in 4) above.

The second group provides instantaneous wheel/rail forces as follows:

FF	Lateral flange forces	(lb)
FCX	Longitudinal Tread Creep forces	(lb)
FCY	Lateral Tread Creep forces	(lb)
FWZ	Vertical Wheel loads	(lb)

The twelve values given are for the six left wheels (axles 1 through 6) and th six right wheels (axles 1 through 6) in that order.

The next group provides, in the same order across the page:

FPX	Longitudinal primary forces	(lb)
FPY	Lateral primary forces	(lb)
FPZ	Vertical primary forces	(lb)

and these are followed by the forces and moments at the secondary suspension for the lead and trail trucks:

FSY	Lateral secondary force	(lb)
FSZ	Vertical secondary force	(lb)
MSX	Secondary roll moment	(in-lb)
MSY	Secondary pitch moment	(in-lb)
MSZ	Secondary yaw moment	(in-lb)

Following these suspension forces and moments are listed the relative displacements (or rotations) and velocities at the interconnections:

YW	Wheelset/rail lateral displacement	(in)
DYW	Wheelset/rail lateral velocity	(in/sec)
THETW	Wheelset/rail yaw rotation	(radians)
DTHETW	Wheelset/rail yaw velocity	(radians/sec)
YP	Primary lateral displacement	(in)
DYP	Primary lateral velocity	(in/sec)
ZP	Primary vertical displacement	(in)
DZP	Primary vertical velocity	(in/sec)
YS	Secondary lateral displacement	(in)
DYS	Secondary lateral velocity	(in/sec)

These are followed by the non-dimensional slip velocities of the wheelsets (WN) and the secondary yaw data:

THETS	Secondary yaw rotation	(radians)
DTHETS	Secondary yaw velocity	(radians/sec)

The next three lines of data provide the instantaneous data on the state variables (displacements and rotations, velocities, and accelerations).

The balance of the data relates to the L/V ratios:

FL	net lateral force outward on rail	(lb)
FV	net vertical force on rail	(lb)
EC(12)	individual wheel L/V ratios	(ND)*
EC(6)	wheelset L/V ratios	(ND)
EC(4)	truckside L/V ratios	(ND)

* Non Dimensional

b) SPLOT

The output to disc for off-line processing is not usually displayed, but must be referenced by index number for the off-line plotting. Exhibit 3.3.2.5.1 shows the index numbers. Exhibit 3.3.2.5.2 is a sample output showing a plot of the body vertical displacement (Z). As shown, the index for this variable is 181.

```
T=  2.99900    TPFLAG( 1)=  0.  TPFLAG( 2)=  0.  TPFLAG( 3)=  0.  TPFLAG( 4)=  0.  TPFLAG( 5)=  0.

FF     -17513.   -9671.        0.  -17430.   -9406.        0.        0.        0.        0.        0.        0.        0.
FCX       757.     599.    -1400.     770.     599.    -1061.     -757.     -599.     1400.     -770.     -599.     1061.
FCY      8495.    5299.     -314.    8492.    5199.     -390.     8367.     5360.     -310.     8379.     5263.     -385.
FMZ     33847.   33344.    33943.   34170.   33675.    34348.    33247.    33859.    33362.    33632.    34236.    33665.

FPX      2072.    1953.      448.    2078.    1949.      699.      928     1047.     2552.      922.     1051.     2301.
FPY       -30.    1009.      -41.      37.     994.     -235.     -605.       -6.     -566.     -580.       77.     -526.
FPZ     27046.   27096.    27151.   27400.   27450.    27506.    26924.    26984.    27030.    27278.    27337.    27384.

FSY                          -221.                                                   -214.
FSZ                        162231.                                                 164354.
MSX                         12270.                                                  12333.
MSY                       -230159.                                                -230159.
MSZ                             0.                                                      1.

YW                -.769              -.671              -.220              -.766              -.668              -.296
DYW                .001               .004               .022              -.002               .003               .095
THETW            -.00698            -.00340             .00019            -.00667             -.00328            .00030
DTHETW           -.00011            -.00011            -.00011            -.00018             -.00018           -.00018

YP                -.119               .210              -.109              -.126               .189              -.060
DYP               -.007              -.002              -.010               .009               .019              -.059
ZP      -.027     -.018    -.008      .036     .046     .055     -.059      -.049     -.040      .005      .014      .024
DZP     -.005     -.005    -.005     -.006    -.006    -.007      .013       .013      .013      .012      .012      .012

YS                         -.03066                                                 -.03102
DYS                         .06141                                                  .06460

WN                -.000               .000               .000              -.000               .000               .000
THETS                      -.00861                                                  .01536
DTHETS                      .00007                                                  .00014

  Y(1)    Y(2)    Y(3)     Y(4)     Y(5)     Y(6)     P(1)     P(2)   THET(1)  THET(2)     Y        Z       ALF      BET      EAN
 .77E+00 .82E+00 .22E+00  .77E+00  .81E+00  .30E+00  .61E+00  .63E+00  .34E-02  .33E-02  .67E+00  .18E-02 -.40E-03 -.12E-03 -.22E-04
-.62E-03-.38E-02-.22E-01  .24E-02 -.25E-02 -.95E-01 -.23E-02 -.22E-01  .11E-03  .18E-03 -.88E-01 -.34E-02  .23E-03  .24E-05  .41E-04
 .11E-01 .49E-01 .36E-01  .96E-02  .59E-01  .83E-01 -.91E-02  .79E-02 -.64E-04  .58E-04 -.77E-01  .62E-02  .17E-02 -.43E-05 -.60E-04

FL       9019.    4372.     314.    8939.    4207.     390.     8367.     5360.     -310.     8379.     5263.     -385.
FV      33847.   33344.   33943.   34170.   33675.   34348.    33247.    33859.    33362.    33632.    34236.    33665.

EC(12)      .266     .252     .131     .158     .005    -.009      .262      .249      .125      .154      .011     -.011

EC(6)           0.                -0.                0.                 0.                -0.                0.

EC(4)                    0.                           0.                           0.                            0.
```

Variable numbering system for plotting

```
  2 to  13
 14  "  25
 26  "  37
 38  "  55
 56  "  61
 62  "  73
 74  "  85
 86  "  87
 88  "  89
 90  "  91
 92  "  93
 94  "  95
 96  " 101
102  " 107
108  " 113
114  " 119
120  " 125
126  " 131
132  " 143
144  " 155
156  " 157
158  " 159
160  " 165
166  " 167
168  " 169
170  " 184
185  " 199
200  " 214
215  " 226
227  " 238
239  " 250
251  " 256
257  " 260
```

ORIGINAL PAGE IS
OF POOR QUALITY

EXHIBIT 3.3.2.5.1 - AVAILABLE OUTPUT VARIABLES

ORIGINAL PAGE IS OF POOR QUALITY

PLOTTING PROGRAM

RUN #: 1 DATE: 80/08/11. 13.52.02.

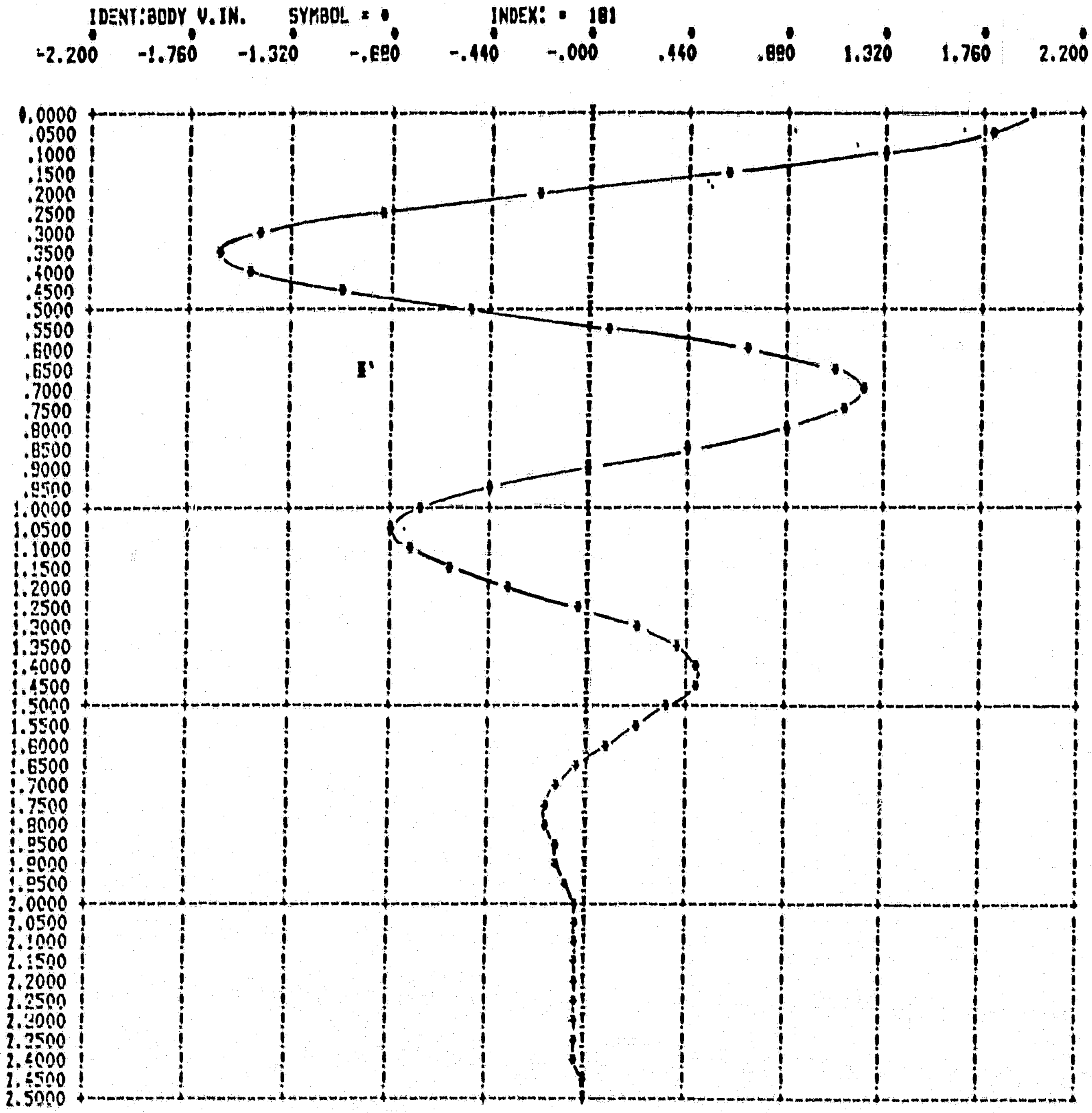

EXHIBIT 3.3.2.5.2 - SAMPLE PLOT OUTPUT:
BODY VERTICAL DISPLACEMENT (IN.)
VERSUS TIME (S)

3.4 COMPUTER RESOURCE REQUIREMENTS

The program has been run on a CDC Cyber 174 computer under control of the NOS operating system. The definition of the required resources in terms of memory and computing time relates specifically to this machine.

Although the time of execution depends upon the compiler in use, the rule of thumb is that a typical FORTRAN program will run approximately six times faster on the 174 than on an IBM 360. This may help to provide a guideline to those not familiar with CDC hardware.

On the CDC Cyber 174, the program requires approximately 13 seconds of computer time and 60K words of memory for compilation and loading using the standard FORTRAN compiler.

Execution of the program requires 18K words of memory and approximately 11 seconds of computer time per second of simulation. Additional time of about 0.75 seconds per second is required for each defect and about 0.1 seconds per output (from SPLOT).

Define:

t_t = total time to be simulated (seconds)
N_d = total number of defects specified
N_p = number of SPLOT outputs per simulated second

Then we can approximate the CPU time (t_{cpu}) by:

$$t_{cpu} \simeq t_t \left\{ 11. + (.75)\ (N_d) + (0.1)\ (N_p) \right\}$$

On the CDC Cyber 174, our experience for typical runs indicates a cost of between one and two dollars per simulated second.

Appendix 4 - Technical Description of the Model

	Pg
4.1 Introduction	4-1
4.2 Coordinate System and Degrees of Freedom	4-3
4.3 Description of Suspension Elements	4-5
4.4 Forcing Functions	4-15
4.5 Measures of Safety	4-18
4.6 Equations of Motion	4-20

Appendix 4

APPENDIX 4

TECHNICAL DESCRIPTION OF THE MODEL

4.1 INTRODUCTION

The methodology contains an analytic model of a locomotive which consists of a vehicle resting on two 3-axle trucks. Figure 4.1 is a side-elevation view of the model (rear truck not shown), and Figure 4.2 is the corresponding end-view. These diagrams are designed to highlight the interface regions between the major functional parts of the locomotive suspension system, namely, the secondary suspension between the vehicle body and the truck frame, the primary suspension between the truck frame and the wheelsets, and the wheel-rail interface.

Also shown in Figures 4.1 and 4.2, are some of the important dimensions that have an influence on the dynamic behavior of the locomotive. The definitions of these and other symbols that are being used in the modelling can be found in the technical description that follows. It is sufficient here to discuss a few of them, in order to point out some fundamental features in the model.

- The axles of a truck are equally spaced; hence the half truck wheelbase ℓ.

- The center of gravity of the truck frame is assumed to be located vertically above the center axle.

- The center of gravity of the vehicle is assumed to be located midway between the center of gravity of the two trucks: hence the longitudinal truck center distance, 2L.

- Whenever coupling is to be considered (whether fore or aft or both) coupler forces will be acting on the corresponding coupler-pin(s); the pins are assumed to be located at a distance D longitudinally from the center of gravity of the vehicle, and at a distance h_p above the rail-head.

- The tractive effort T_e of the locomotive is assumed to be contributed by equal amounts at each of the 6-axles. Braking force is treated as a negative tractive effort. Within a single test run, the tractive effort is assumed to be constant in magnitude.

- The locomotive is assumed to travel at a volicity V which is constant during any single test run.

- The track has nominal and constant values for curvature (D_c), absolute superelevation σ, and kinematic gauge 2b.

- Irregularities in the track geometry are supplied as input parameters. The irregularities covered are lateral alignment, vertical alignment, cross-level, and track gauge.

As a result of disturbances transmitted via the track or other external forces, the locomotive (vehicle, trucks, wheelsets) is set in different modes of vibrations, and forces are generated at the various interfaces. These interfaces or suspension forces are treated in Section 4.3. Track

geometry defects are described in Section 4.4, as well as other forcing functions such as coupler and wind loads.

This is followed by a description of the measures of safety in Section 4.5, and the equations of motion in Section 4.6.

4.2 COORDINATE SYSTEM AND DEGREES OF FREEDOM

Figure 4.3 shows schematically the plan view of the locomotive at equilibrium on an ideal track with constant radius of curvature R_c. Because of the track curvature, the center of gravity of the vehicle and the trucks (A, B, and C, respectively), are all offset from the track. At this position of equilibrium, the center of gravity of each truck is displaced towards the center of the curvature of the track by an amount

$$\Delta = \frac{\ell^2}{2R_c}$$

The reference systems and the degree of freedom of the vehicle and of the trucks are defined as follows.

1) Vehicle

The origin of the Cartesian reference system coincides with the center of gravity of the vehicle, with the x-axis pointing along the longitudinal axis of the vehicle, and with the x-y plane horizontal. See Figure 4.1 and Figure 4.3. The z-axis points vertically upwards, while the y-axis points away from the center of track curvature.

Since constant train velocity is assumed, there are five permissible degrees of freedom associated with the vehicle body:

y - vehicle lateral

z - vehicle vertical

α - vehicle roll

β - vehicle pitch

γ - vehicle yaw

The rotational movements follow the right-hand corkscrew sign convention about the x, y and z axes, respectively

2) <u>Trucks and Wheelsets</u>

The reference system of the leading truck frame and its wheelsets (identified as 1, 2, and 3, starting from the leading position) has an origin coinciding with the truck frame center of gravity.

There are two degrees of freedom associated with the leading truck frame:

p_1 - truck lateral, oriented along the radius of curvature OB and away from the center O,

θ_1 - truck yaw, about the vertical axis through the center of gravity, and observing the right-hand rule as shown.

The wheelsets have one degree of freedom each, namely, lateral displacements y_1, y_2, and y_3, all defined parellel to the radius of curvature, and measured from the center of gravity.

The reference system of the trailing truck frame and its wheelsets, 4, 5, 6, are defined in a manner similar to that of the leading truck.

It should be noted that truck motions in the vertical, pitch, and roll directions are assumed to be constrained to those of the locomotive body at the secondary suspension. This assumption is considered valid when the secondary suspension stiffness is significantly higher than the primary suspension stiffness in those modes. Another assumption is that the wheelsets are constrained in yaw to the truck frame. This assumption is considered valid provided the longitudinal pedestal clearances are small.

4.3 DESCRIPTION OF THE SUSPENSION ELEMENTS

4.3.1 Definitions and Nomenclature System

The locomotive suspension elements can be classified with respect to three interfaces as follows:

Interface	Upper Part	Lower Part
secondary suspension	vehicle	truck frame
primary suspension	truck frame	wheelset
wheel-rail	wheel	rail-head

The nomenclature system used to define the interface forces is as follows.

Secondary suspension:

F_{sx_k} = secondary longitudinal force

F_{sy_k} = secondary lateral force

F_{sz_k} = secondary vertical force

M_{sx_k} = secondary roll moment

M_{sy_k} = secondary pitch moment

M_{sz_k} = secondary yaw moment

Notes: F = Force, M = moment, s = secondary,
x, y and z denote direction,
k = 1, 2 for leading and trailing truck respectively.

Primary suspension:

$F_{px_{i,j}}$ = primary longitudinal force

$F_{py_{i,j}}$ = primary lateral force

$F_{pz_{i,j}}$ = primary vertical force

Notes: F = Force, p = primary suspension,
x, y and z denote direction,
i = 1, 6 denotes wheelset identification,
j = 1, 2 for left and right sides respectively.

Wheel-rail interface:

$F_{wz_{i,k}}$ = vertical wheel-rail force

$F_{cx_{i,j}}$ = longitudinal creep force

$F_{cy_{i,j}}$ = lateral creep force

$F_{f_{i,j}}$ = lateral flange force.

Notes: F = Force, w = wheel,
c = creep, f = flange,
x and y denote direction,
i,j = same as for primary.

To facilitate visualizing how these forces act in the locomotive model, an exploded free-body diagram is shown in Figure 4.4.

4.3.2 Secondary Suspensions Characteristics

1) Secondary Lateral F_{sy}

The secondary suspension lateral forces at the leading and the trailing trucks are each made up of four components:

a) a component due to the nonlinear stiffness of the rubber elements and the limiting stops,

b) a second component due to linearized viscous damping of the rubber material,

c) a third component due to the frictional properties of bolster on the truck traction pads,

d) a fourth component due to external hydraulic dampers when specified.

The nonlinear stiffness of the secondary suspension is modelled as a piecewise linear function of the relative lateral displacement y_{sk} as shown in Figure 4.5. It is characterized by a slope, K_{sy} due to the rubber elements, and a much steeper slope K_{stop} when the spring travel is exceeded and the stop is reached.

The Coulomb friction properties of the traction pads is modelled as a function of relative lateral velocity in the secondary suspension with a linearized viscous band (LVB) followed by saturation. (See Figure 4.6, where the LVB has a slope of K_{f2} and a saturation of F_{ok}). The value of saturation depends on the limiting friction due to the longitudinal secondary force F_{sx}.

2) Secondary Yaw M_{sz}

The secondary yaw moment M_{sz} at either truck is due to the rotational friction encountered at the center-plate of the truck. A LVB model similar to that of Figure 4.6 is used for this friction which is a function of the relative rotational velocity between the truck frame and the vehicle body. The saturation level is itself a linear function of the vertical secondary suspension force F_{sz}.

3) <u>Secondary Longitudinal F_{sx}</u>

The secondary longitudinal forces acting at the center-plate of the leading truck (F_{sx1}) and of the trailing truck (F_{sx2}) together balance the sum of all external forces acting on the locomotive. Assuming no dynamics for the locomotive in the longitudinal direction,

$$F_{sx1} = F_{sx2} = \tfrac{1}{2} \text{ (total tractive effort } T_e\text{)}.$$

As mentioned earlier, a braking effort is treated like a negative tractive effort.

4) <u>Secondary Vertical F_{sz}</u>

Assuming no independent vertical dynamics of the individual truck frames, the vertical force F_{sz} acting at the secondary suspension of the locomotive is equal to the sum of all the primary vertical forces F_{pz} on a given truck.

5) <u>Secondary Roll M_{sx}</u>

The secondary roll moment M_{sx1} acting on the leading truck is the result of the sum of roll moments acting on the truck frame due to the primary vertical forces and primary lateral forces.

6) <u>Secondary Pitch M_{sy}</u>

The secondary pitch moment at each truck is found by considering the balance of pitch moments acting on the truck frame due to the action of primary vertical forces, and the tractive effort.

4.3.3 Primary Suspension Characteristics

1) Primary Lateral F_{py}

The lateral force F_{py} generated at each journal box is due to a nonlinear stiffness characteristic in addition to friction forces developed in the roller bearing. The primary lateral stiffness is based on element tests on the resilient thrust unit. The test data are simplified and represented by the curve OABC as shown in Figure 4.7. The first portion of this curve, OA, approximates a freeplay region of magnitude d_1. This is followed by a polynomial stiffness AB, covering a working range of permissible bearing movement d_2. The value P_h at A represents a preload on the rubber unit of typically 1500 lb. Beyond this range, a hard stop is reached, exhibiting a very steep load-displacement relationship BC.

The frictional component of the primary lateral force is modelled again by a LVB as depicted in Figure 4.6. The saturation level, due to a limiting frictional force, is based on the resultant of the primary vertical and the primary longitudinal forces acting at the bearing in question. A coefficient of friction of 0.1 is normally used.

2) Primary Vertical F_{pz}

The vertical force F_{pz} acting at the end of each axle is made up ot three components:

a) a stiffness component due to spring stiffness and a limiting stop,

b) a component due to pedestal face and pedestal side lug friction,

c) a component due to an external damper, when specified.

The stiffness is characterized by a piecewise linear curve as shown in Figure 4.8. It consists of a central segment of slope K_1 representing the spring stiffness. It is terminated at both ends by a steeper slope K_s representing the end of vertical travel of the spring. The suspension is preloaded by an amount F_{Ko}, which nominally is equal to a share of the total sprung load of the locomotive. Since there are 12 journals per locomotive,

$$F_{Ko} = (W_v + 2W_t) / 12$$

where W_v = weight of vehicle
W_t = weight of truck frame and bolster.

The pedestal friction is modelled by a LVB, where the saturation level is made up of contributions of friction due to the primary longitudinal force F_{px} and due to the primary lateral force F_{py}. Thus

$$\text{saturation level } F_{do} = \mu_x \left| F_{px} \right| + \mu_y \left| F_{py} \right| .$$

where μ_x and μ_y are the frictional coefficients acting at the surfaces of contact in question.

Wherever there is an external vertical damper in the primary suspension, the nonlinear characteristics in Figure 4.9 are used. It is simply an asymmetrical LVB, with damping coefficients C_3 in one direction of travel, and C_4 in the other. The saturation levels may also assume different values (f_3, f_4).

NOTE: PRIMARY VERTICAL FORCES FOR THE E-8 LOCOMOTIVE TRUCK

In the case of the E-8 locomotive, different equations are used to represent the truck. The E-8 truck features complete "wheel load equalization" (equalizer bars and primary springs located at an intermediate location between the wheelsets) and a secondary suspension which is softer than the primary. For this truck configuration, therefore, the parameters used to define the primary stiffness are obtained from considerations of equivalent stiffnesses of springs connected in series as follows:

$$\frac{1}{k_e} = \frac{1}{k_p} + \frac{1}{k_s}$$

where, k_e = equivalent vertical primary stiffness used in the model

k_p = measured primary suspension stiffness

k_s = measured secondary suspension stiffness

To account for the load equalization feature (i.e. wheel loads are not affected by quasi-static differences in crosslevel or surface defects within the truck wheelbase), the vertical primary stiffness forces are assumed to be equal within each side of each truck (i.e. there can only be four different values of primary vertical spring force per locomotive).

These spring forces are obtained from average track cross-level and vertical track geometry under each truck.

The velocity dependent forces (i.e. pedestal friction) are treated in the same manner as for a non-equalized truck.

3) Primary Longitudinal F_{px}

The primary longitudinal forces are obtained by considering force and moment balance on each wheelset in a horizontal plane passing through the wheelset geometric center. Longitudinal pedestal forces result from longitudinal creep forces, tractive effort, and inertial reaction forces resulting from accelerations of the wheelset/traction motor assembly in the lateral and yaw directions.

4.3.4 Wheel-rail Interface

1) Vertical Wheel Loads F_{wz}

The vertical wheel-rail forces are obtained by considering force and moment balance on each wheelset in a transverse vertical plane. Vertical wheel loads result from primary vertical forces, creep and flange forces, and inertial reaction forces resulting from track accelerations in the vertical and cross-level directions.

2) Wheel-Rail Creep Forces F_{cx}, F_{cy}

A non-linear creep force formulation is used, which is based on the wheel-rail contact geometry, the creepages at the contact points, the wheel-rail Coulomb friction coefficient, and the instantaneous normal tread force on each wheel. The formulation is:

$$F_c = \left\{ 1 + \left[\frac{f\varepsilon}{3\mu F_{wz}} - 1 \right]^3 \right\} \mu F_{wz}$$

where: ε = total creepage

μ = wheel-rail friction

f = creep coefficient

as shown in Figure 4.10.

The creep coefficients are assumed to be equal in the lateral and longitudinal directions. This value is however dependent on the instantaneous wheel-rail vertical force as follows:

$$f = G \pi ab$$

where G = shear modulus ($11.5 \times 10^6 \frac{\text{lb}}{\text{in}^2}$)

a, b = semi-axis of the wheel-rail contact area (classic Hertz contact theory).

Having obtained the total creep force, the longitudinal and lateral components are, respectively:

$$F_{cx} = F_c \cdot \frac{\varepsilon_x}{\varepsilon}$$

$$F_{cy} = F_c \cdot \frac{\varepsilon_y}{\varepsilon}$$

ε being the vector sum of the longitudinal and lateral creepage components ε_x and ε_y, respectively. The creepage components are computed from simple geometric relationships, taking account of the following:

- track curvature and gauge,
- locomotive speed,
- wheelset angle of attack and angular velocity,
- wheelset deflection from track centerline and lateral velocity,
- wheel tread conicity, rolling radius, and tape size mismatch as specified for each wheelset,
- wheelset rotational slip (resulting from tractive effort).

3) Lateral Flange Contact Forces F_f

When the wheelset is displaced laterally, the flange of one wheel touches the rail after the flangeway clearance is traversed. Further displacement will result in increasing contact force which can be modelled as a linear spring force. The flange clearance may deviate from the nominal value according to the local track gage variation at that point as described in the following section.

4.4 FORCING FUNCTIONS

4.4.1 Track Geometry

In addition to the nominal geometry, consisting of curvature superelevation and standard track gage, track

geometry irregularities are considered. Track geometry irregularities are defined as a summation of defects which are superimposed at the time of computation. Each defect is defined by the following:

- identification number (1,2,3,etc.)
- starting point along track
- type (cross-level, lateral, vertical, or gage variation)
- class (versine, or others)
- characteristic length (e.g. wavelength)
- characteristic amplitude
- number of repeated cycles.

For each individually specified defect, the track input is computed using an expression of the form: (e.g. for versine)

$$q_t\ (x) = \frac{Q}{2} \left\{ 1 - \cos \left[2\pi\ \frac{(x - xs)}{(xe - xs\ )} \right] \right\}$$

where x = position along track

xs, xe = start and end position of the defect

Q = amplitude

The instantaneous position of each wheelset is computed from the current simulated time, the locomotive speed, and the wheelset spacings.

4.4.2 Other Forcing Functions

The other factors that are included in the model as additional input functions are:

- tractive effort T_e
- wind load F_w
- coupler loads F_d
- superelevation deficiency force F_g

1) Tractive Effort T_e

The tractive effort T_e acts on the locomotive in the longitudinal direction at the three suspension levels. Traction provided by the traction motors is a positive tractive effort, while braking is regarded as a negative tractive force.

2) Wind Load F_w

A lateral wind force acting on the vehicle is considered. The wind load is assumed to act at the specified center of pressure for the locomotive.

3) Lateral Coupler Forces F_d

Lateral components of coupler forces can be specified at each coupler (i.e. leading and trailing ends). Presently, only a constant level of force can be specified which is applied throughout the simulation.

4) Superelevation Deficiency F_g

For a given superelevation, if the locomotive speed V is greater or less than the balance speed, superelevation deficiency prevails in the form of lateral loads acting through the center of gravity of the vehicle (F_{gv}), the truck frames (F_{gt}), and each of the wheelset and traction motion subassemblies

(F_{gw}). This load is calculated as follows:

$$F_g = m\left(\frac{V^2}{R_c} - g\alpha_o\right)$$

where m = mass

V = train speed

α_o = nominal superelevation angle

R_c = radius of track curvature

g = gravitational constant

4.5 MEASURES OF SAFETY

Measures of safety are computed simply from the instantaneous values of net lateral and vertical wheel-rail forces. Individual lateral and vertical wheel forces are obtained as follows:

$$V = F_{wz}$$

$$L = \pm \left\{F_f + F_{cy}\right\}$$

where the sign of the lateral wheel force is defined as positive when directed away from track centerline.

The measures of safety are computed as follows:

1) Wheel L/V Ratio

"Wheel L/V" $= \frac{L}{V}$

This is performed for each wheel for a subtotal of 12 measures of safety.

2) Wheelset L/V Ratio

$$\text{"Wheelset L/V"} = \frac{L \text{ left} - L \text{ right}}{V \text{ left} - V \text{ right}}$$

where left and right refer to the position of the wheel. This is performed for each wheelset. Since wheelset L/V ratio requires to be monitored for both positive values (towards outer rail) and negative values (towards inner rail) this gives a subtotal of 12 measures of safety.

3) Truck Side L/V Ratios

$$\text{"Truck side L/V"} = \frac{L \text{ lead} + L \text{ center} + L \text{ trail}}{V \text{ lead} + V \text{ center} + V \text{ trail}}$$

where lead, center, trail refer to the wheelset position within a truck. This is performed for each truck and each side for a subtotal of four measures of safety.

In summary, a grand total of 28 measures of safety are monitored for peak value analysis.

The instantaneous values of measures of safety are processed through a numerical averaging filter before analysis, for peak values. A simple "running average" technique is used over a time duration τ_f. The value of τ_f is currently set to 50 msec. for all measures of safety, but can be altered as specified.

4.6 EQUATIONS OF MOTION

4.6.1 Nomenclature

The following nomenclature is used in the equations of motions. For the definition of the subscripting system of forces and moments, refer to sections 4.3.1 and 4.4.2.

m_v = locomotive body mass

m_z = locomotive body mass including truck frame masses

m_t = truck frame mass

m_i = mass of wheelset/traction motor assembly

Icx, Icy, Icz = effective mass moment of inertia of locomotive body about the center of gravity, in roll, pitch, and yaw respectively

I_t = effective mass moment of inertia of truck assembly in yaw

g = gravity constant

h_1 = height of secondary suspension above rail

h_2 = height of body center of gravity above secondary suspension

h_d = vertical distance between coupler and body center of gravity

h_{wc} = vertical distance between center of pressure (wind load) and body center of gravity

h_p = height of coupler above rail

2b = track kinematic gauge

2ℓ = truck wheel base

2L = truck center distance

2D = distance between coupler pins

e_i = offset of wheelset/traction motor assembly center of gravity from axle centerline.

4.6.2 Equations

The 15 equations of motion are:

1) Vehicle Lateral

$$\ddot{y} = \frac{1}{m_v}\left\{(F_{sy1} + F_{sy2}) + (F_{d1} + F_{d2}) + F_{gv} + F_{wind}\right\}$$

2) Vehicle Vertical Motion

$$\ddot{z} = \frac{1}{m_z}\left\{F_{sz1} + F_{sz2}\right\} - g$$

3) Vehicle Roll Motion

$$\ddot{\alpha} = \frac{1}{I_{cx}}\left\{(M_{sx1} + M_{sx2}) + h_2 (F_{sy1} + F_{sy2}) + h_d (F_{d1} + F_{d2}) - h_{wc} (F_{wind})\right\}$$

4) Vehicle Pitch Motion

$$\ddot{\beta} = \frac{1}{I_{cy}}\left\{(M_{sy1} + M_{sy2}) + L (F_{sz2} - F_{sz1}) - T_e (h_p - h_1)\right\}$$

5) Vehicle Yaw Motion

$$\ddot{\gamma} = \frac{1}{I_{cz}}\left\{(M_{sz1} + M_{sz2}) + L (F_{sy1} - F_{sy2}) + D (F_{d1} - F_{d2})\right\}$$

6) Leading Truck Lateral Motion

$$\ddot{p}_1 = \frac{1}{m_t}\left\{\sum_{i=1}^{3}\sum_{j=1}^{2} F_{pyij} + F_{gt} - F_{sy1}\right\}$$

7) Trailing Truck Lateral Motion

$$\ddot{p}_2 = \frac{1}{m_t}\left\{\sum_{i=4}^{6}\sum_{j=1}^{2} F_{pyij} + F_{gt} - F_{sy2}\right\}$$

8) Leading Truck Yaw Motion

$$\ddot{\theta}_1 = \frac{1}{I_{t1}}\left\{b\sum_{i=1}^{3}(F_{cxi2} - F_{cxi1}) + \ell\sum_{j=1}^{2}(F_{py1j} - F_{py3j}) - M_{sz1} + \sum_{i=1}^{3}\left[e_i\sum_{j=1}^{2}(F_{cyij} + F_{fij} - F_{pyij})\right]\right\}$$

9) Trailing Truck Yaw Motion

$$\ddot{\theta}_2 = \frac{1}{I_{t2}}\left\{b\sum_{i=4}^{6}(F_{cxi2} - F_{cxi1}) + \ell\sum_{j=1}^{2}(F_{py4j} - F_{py6j}) - M_{sz2} + \sum_{i=4}^{6}\left[e_i\sum_{j=1}^{2}(F_{cyij} + F_{fij} - F_{pyij})\right]\right\}$$

10 to 15) i^{th} Wheelset/Traction Motor Subassembly Lateral Motion, $i = 1$ to 6

$$\ddot{y}_i = e_i\ddot{\theta}_k + \frac{1}{m_i}\left\{F_{gwi} + \sum_{j=1}^{2}(F_{cyij} + F_{fij} - F_{pyij})\right\}$$

where $k = 1$ if $i = 1, 2, 3$

$k = 2$ if $i = 4, 5, 6$.

4.6.3 Method of Solution

From considerations of simplicity and convenience during program development and debugging, a simple Euler integration technique was used. Determination of an adequate integration step size was performed empirically by sample problem tests over a wide range of step size values. An integration step size of .001 second was chosen as having a large margin of safety against perturbation of the results.

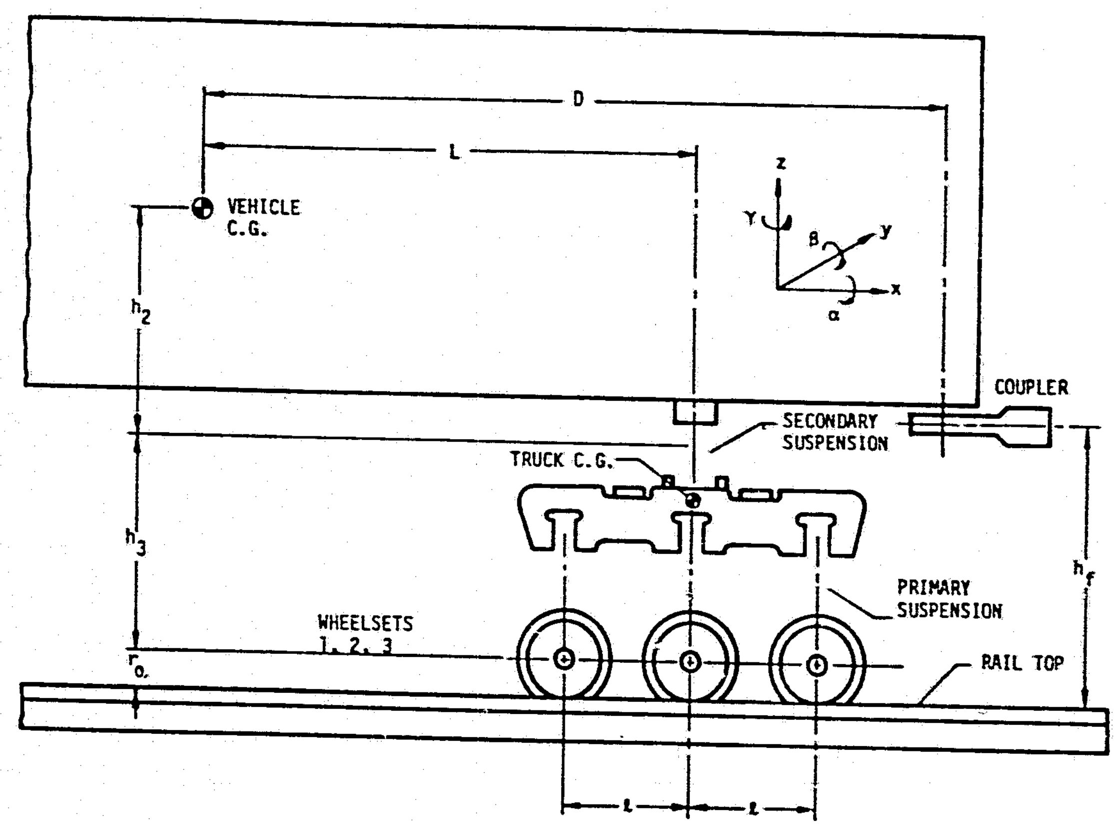

FIGURE 4.1 - SIDE ELEVATION VIEW OF MODEL

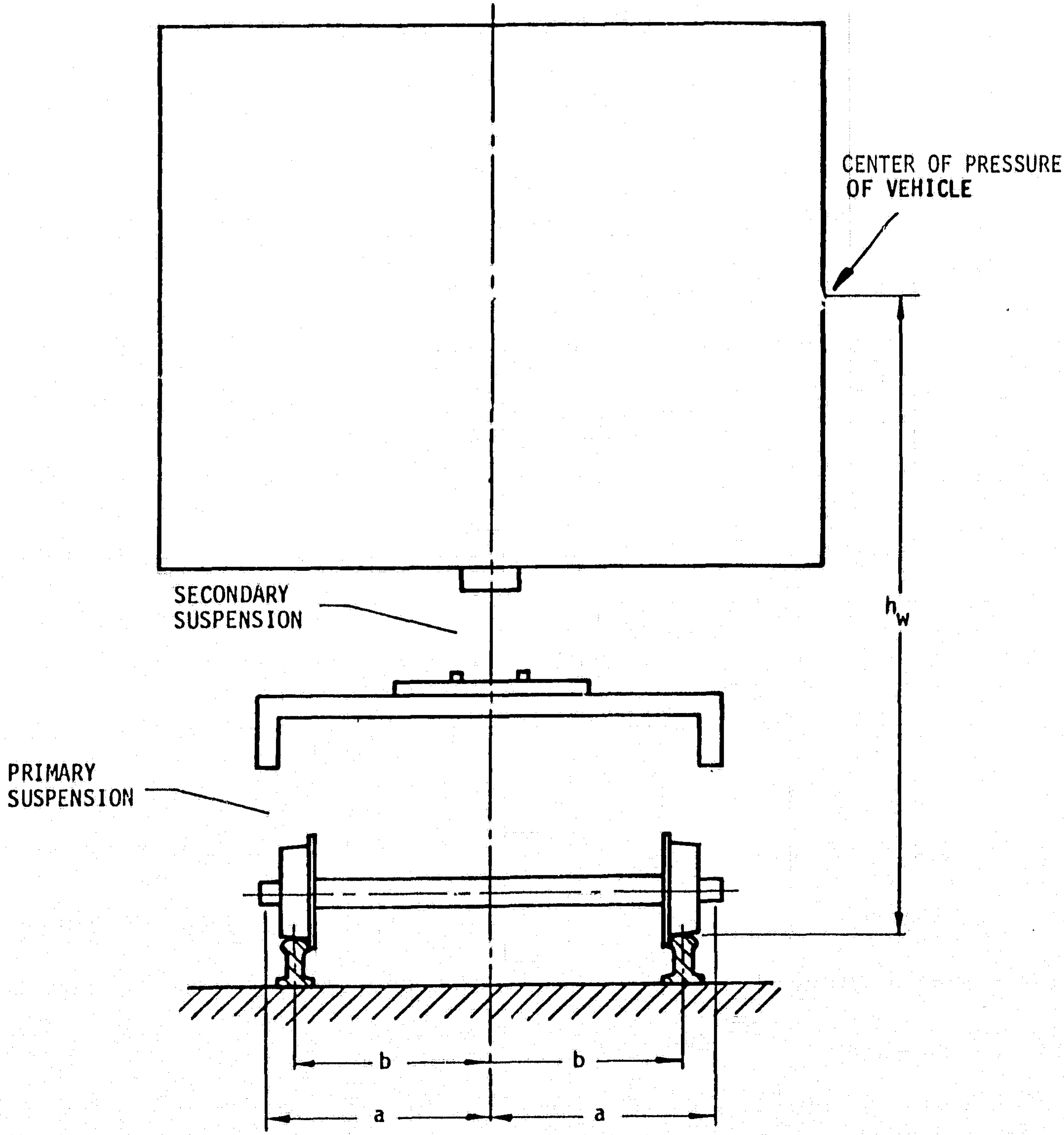

FIGURE 4.2 - END VIEW OF MODEL

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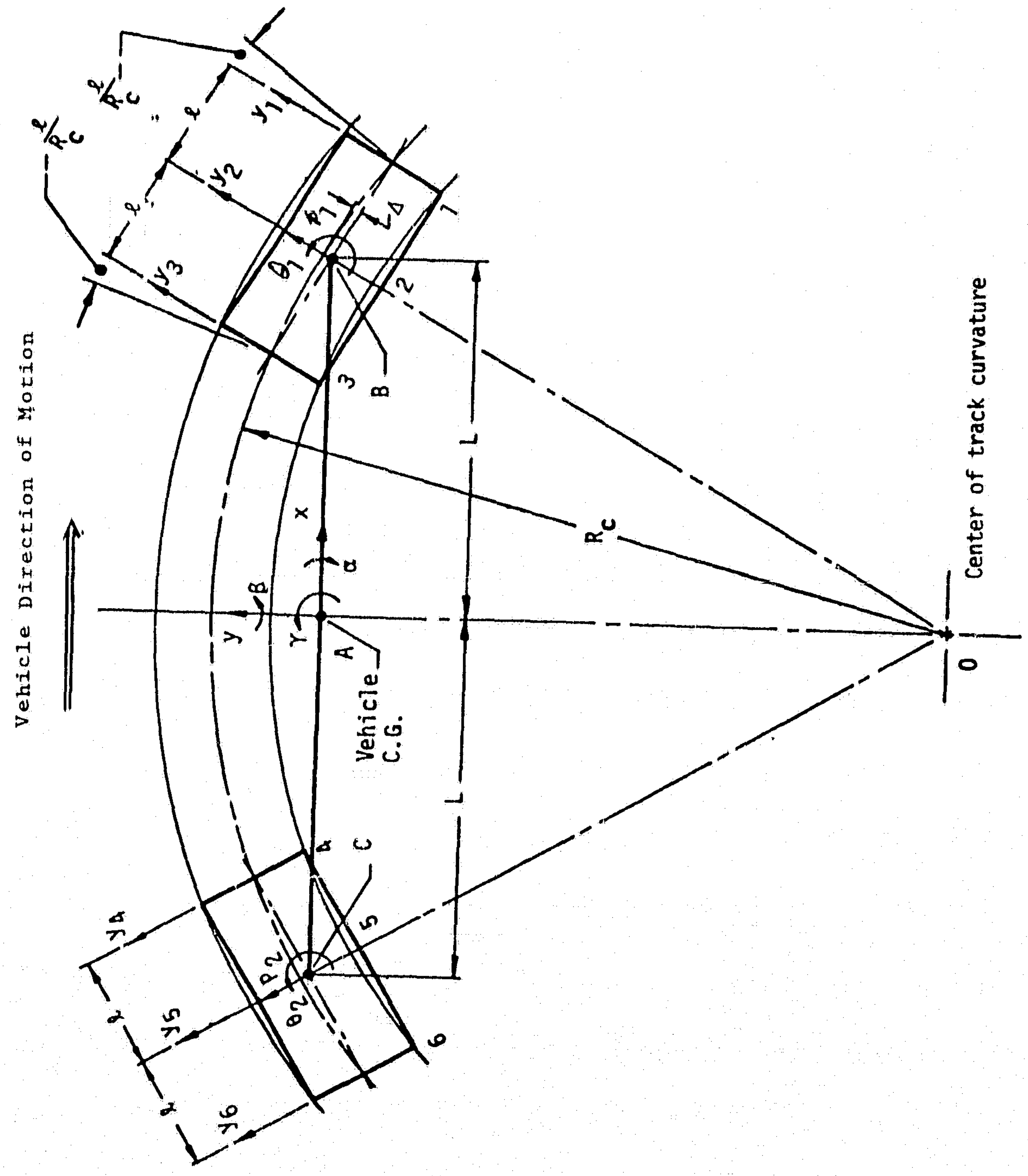

FIGURE 4.3 - ORIENTATION OF COORDINATE SYSTEM

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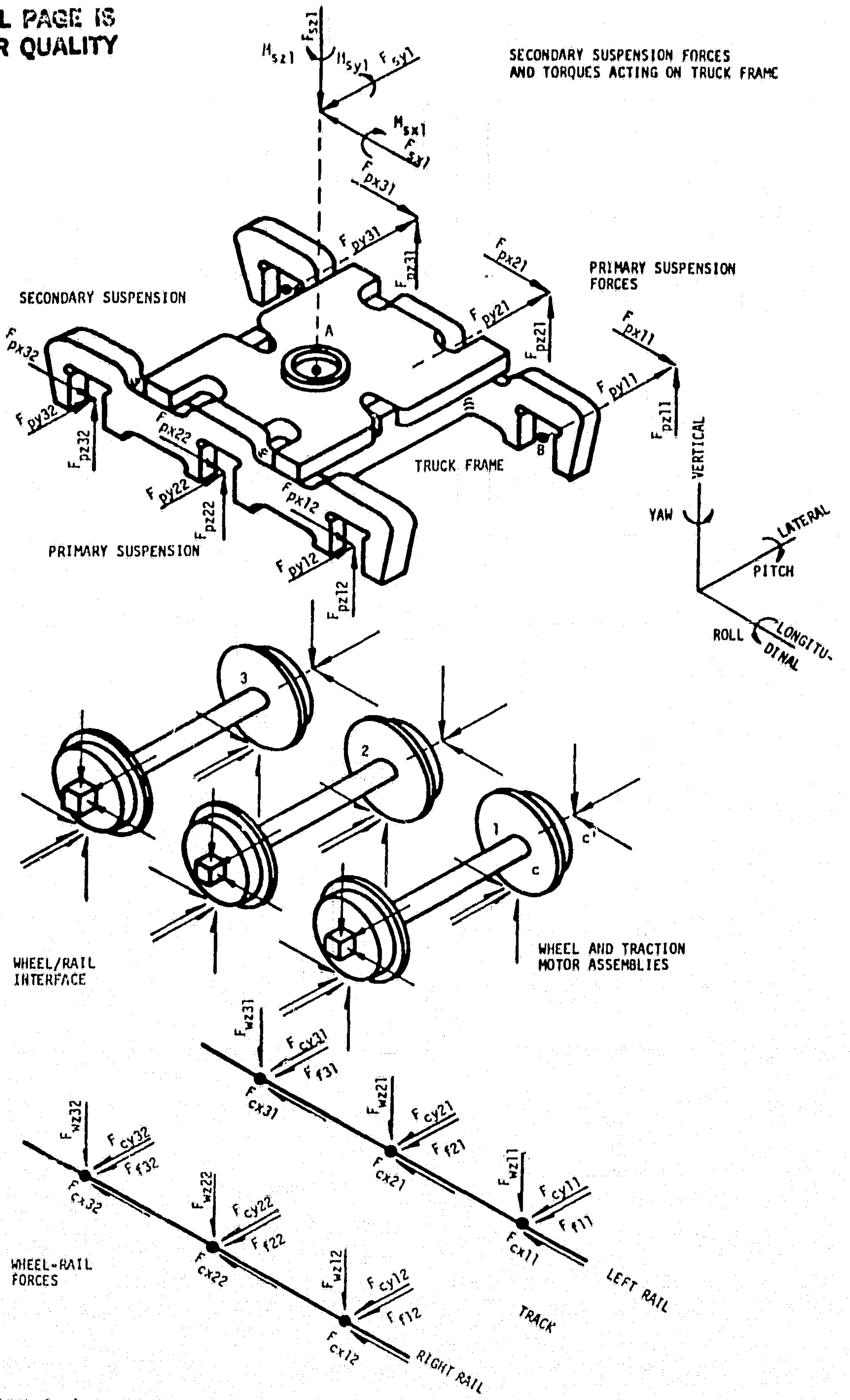

FIGURE 4.4 - SUSPENSION AND WHEEL-RAIL FORCES

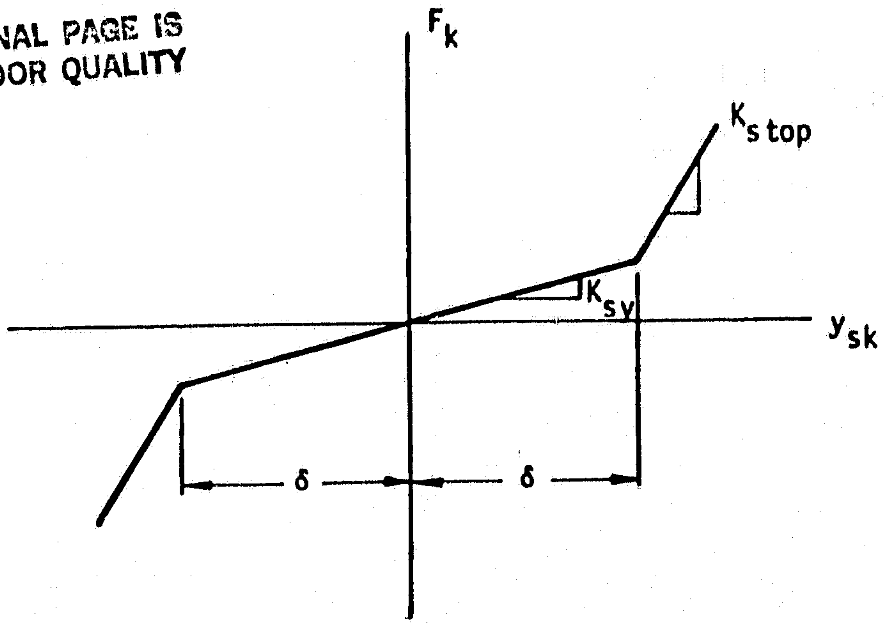

FIGURE 4.5 - SECONDARY LATERAL STIFFNESS CHARACTERISTICS

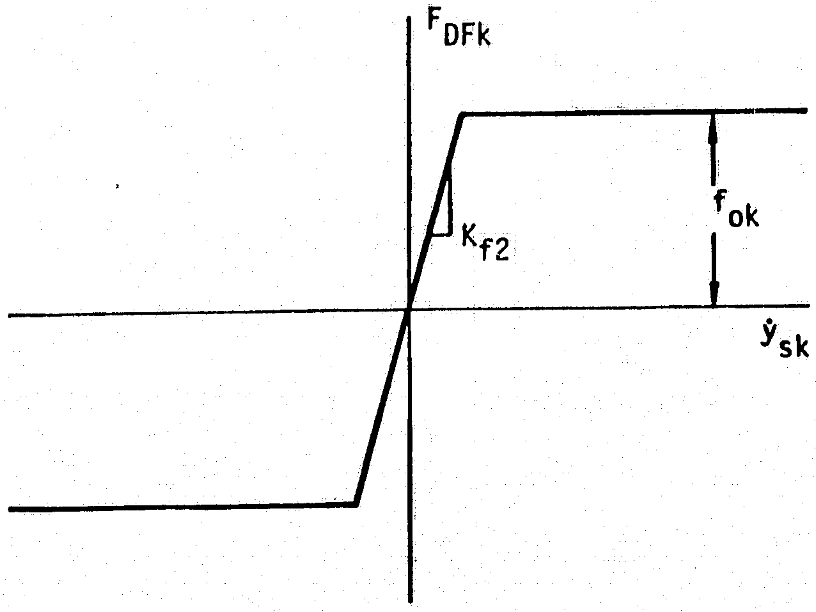

FIGURE 4.6 - LINEAR VISCOUS BAND (LVB) MODEL FOR COULOMB FRICTION

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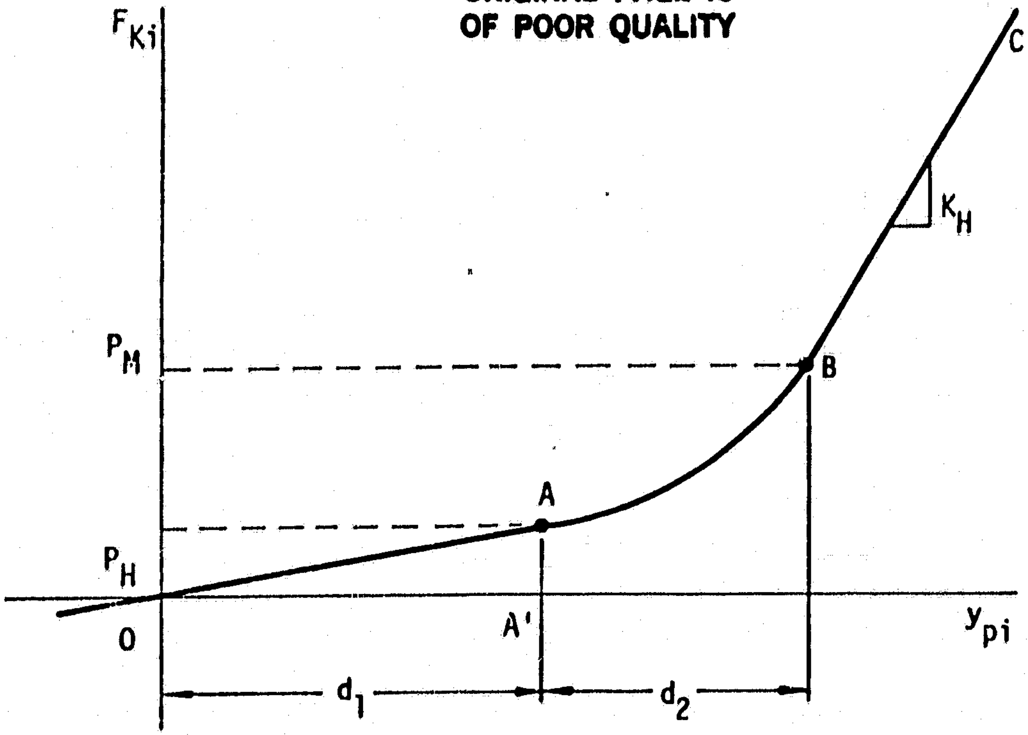

FIGURE 4.7 - PRIMARY LATERAL SUSPENSION CHARACTERISTICS

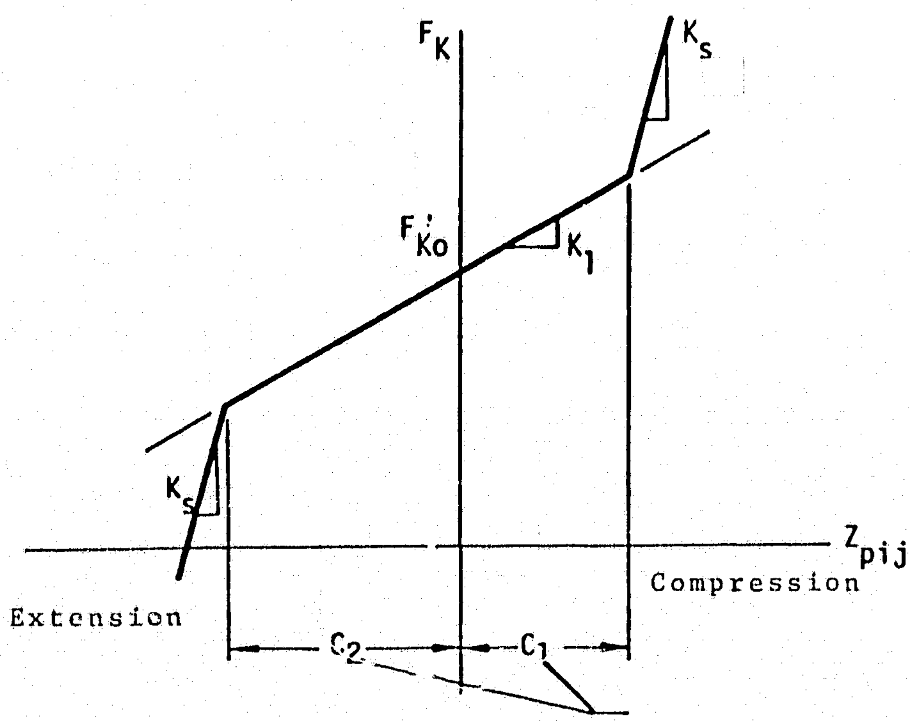

FIGURE 4.8 - PRIMARY VERTICAL SUSPENSION CHARACTERISTICS

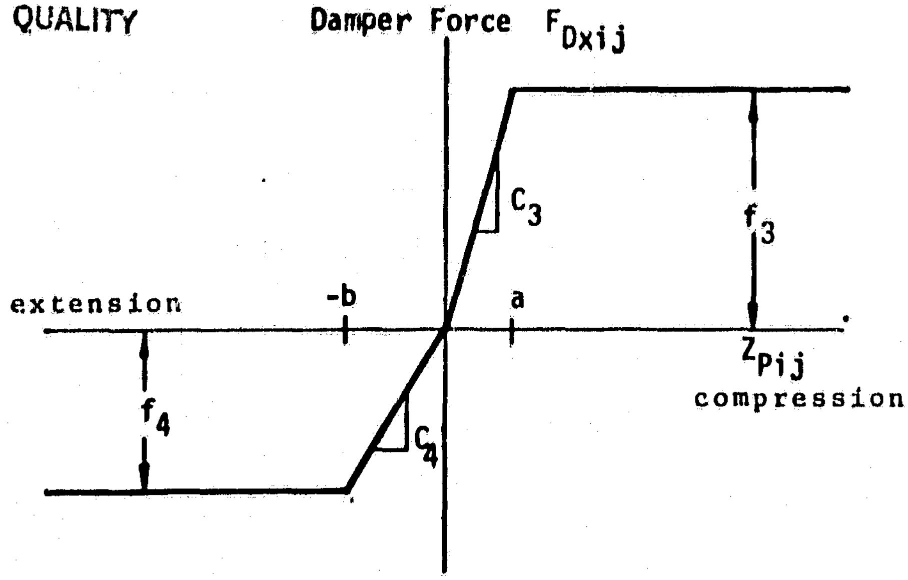

FIGURE 4.9 - EXTERNAL DAMPER CHARACTERISTIC IN THE VERTICAL PRIMARY SUSPENSION

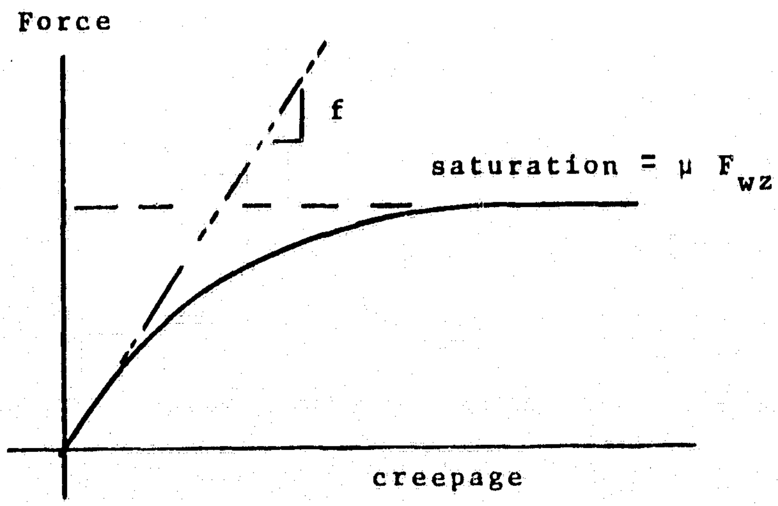

FIGURE 4.10 - WHEEL-RAIL FRICTION CREEP CHARACTERISTIC